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**TRACKING AND DATA RELAY SATELLITE
SYSTEM CONFIGURATION AND TRADEOFF
STUDY-PART II FINAL REPORT**

**Volume I
Summary**

**HUGHES AIRCRAFT COMPANY
Space and Communications Group
El Segundo, California 90009**

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16. Abstract A Tracking and Data Relay Satellite System (TDRSS) concept for service of low, medium, and high data rate user spacecraft has been defined. During the study, four TDRS dual spin stabilized configurations (contractual requirement) were designed; two are compatible with Delta 2914, one with Atlas Centaur, and one with Space Shuttle launches. A summary of the study and the salient results are presented in this volume. The topics included are: TDRSS operations, telecommunications service performance, telecommunications service equipment, TDRS configurations and their design characteristics, and TDRS system reliability.					
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1. INTRODUCTION

The objective of the Hughes Tracking and Data Relay Satellite System (TDRSS) study was to identify an optimum approach for a TDRSS employing dual spin, geosynchronous tracking and data relay satellites, and to define the performance parameters of all elements of the system. The study was divided into two parts: Part I, a 7 month effort to develop a TDRSS concept with service for medium and low data rate users with a TDRS compatible with the Delta 2914 performance and payload envelope constraints; Part II, a 5 month effort, to explore the telecommunications performance potential of TDRSs launched by Atlas class vehicles and the Space Shuttle, and to enhance the telecommunications service of the Delta 2914 launched TDRS. Part I of the study was completed and documented on September 22, 1972. Part II of the study was completed and documented on April 1, 1973.

Applicable experience from current commercial and military space programs has been utilized throughout the study to arrive at an overall system technical approach that stresses simplicity, economy, flexibility, and ease of operations. The TDRS designs make use of a maximum of flight proven design concepts and equipment. Areas which require new technology have been clearly identified.

Maximum use of existing Goddard Space Flight Center network control, scheduling, orbit determination, and data processing capabilities has been planned to enhance the cost effectiveness of the TDRSS.

This volume contains an introduction to the TDRS system concept and a brief summary of system operations, performance, and configurations for the TDR satellite concepts developed during the study:

Delta 2914 launched TDRS configuration 1 (TDRS 1D)

Atlas Centaur launched TDRS configuration (TDRS AC)

Space Shuttle launched TDRS configuration (TDRS SS)

Delta 2914 launched TDRS configuration 2 (TDRS 2D)

For a detailed discussion of these system configurations the following documentation is available:

TDRS 1D	Entire Part I final report
TDRS AC	Volume 3 of Part II final report
TDRS SS	Volume 4 of Part II final report
TDRS 2D	Volume 2 of Part II final report

2. SUMMARY

2.1 SYSTEM CONCEPT

The TDRSS concept uses two operational geostationary satellites and one in-orbit spare to provide relay links for command, tracking, and telemetry between multiple, low earth-orbiting user satellites and a centrally located ground station, as shown in Figure 1, making possible nearly continuous reception of data in real time.

The TDRSS comprises the following major elements:

- GSFC communication control and processing facility
- TDRSS ground station
- TDRS control center
- TDR satellites
- User spacecraft equipment

The communication links from the ground station to the user are defined as forward links, and the links from the user spacecraft to the ground station are defined as return links.

The forward links contain user commands, tracking signals, and voice transmissions; the return links contain the user telemetry, return tracking signal, and voice.

The users are categorized as low data rate (LDR), medium data rate (MDR), and high data rate (HDR), according to their telemetry rates. For LDR service both the forward and return links are implemented with broad coverage (30 degree field of view) antennas. For MDR and HDR service the links are implemented with narrow beam, high gain, steerable antennas.

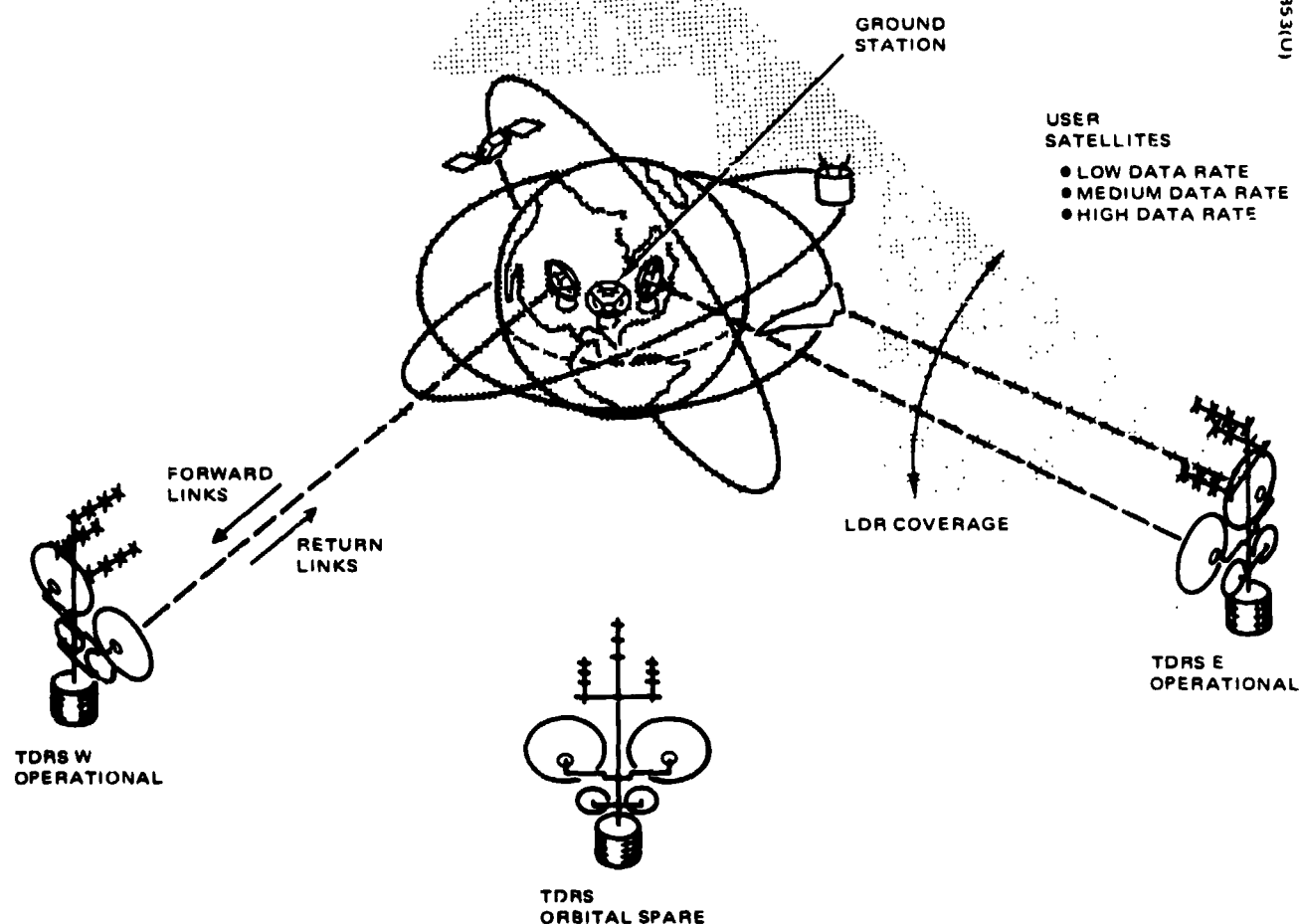


Figure 1. TDRS System Concept

2.2 KEY REQUIREMENTS

The key ground rules defined contractually were:

- Dual spin configuration
- Launch vehicles: Delta 2914, Atlas Centaur, and Space Shuttle
- Minimum TDRS lifetime: 5 years
- Telecommunications service levels as shown in Table 1

TABLE 1. TELECOMMUNICATIONS SERVICE OBJECTIVES

	Forward Link	Return Link
LDR	100 to 1000 bps	100 bps to 10 kbps
MDR	100 to 1000 bps and 2 to 54 kbps ⁽²⁾	10 kbps to 1 Mbps
HDR ⁽¹⁾	2 kbps and 50 Mbps ⁽³⁾	1 to 100 Mbps

(1) Part II only

(2) Space Shuttle requirement

(3) Space Shuttle TV

During the current study effort, discussion with the GSFC program office has led to the conclusion that the following ground rules, although not required contractually, are essential for a viable system concept:

- MDR service compatible with Space Shuttle
- Flux densities for forward links compatible with CCIR regulations
- Maximum use of proven technology and subsystems.

The user services and launch vehicles considered for the two parts of the study are shown in Table 2.

TABLE 2. STUDY ORGANIZATION

	Part I	Part II
Telecommunications service	LDR, MDR	LDR, MDR, HDR
Launch vehicle:	Delta 2914	Delta 2914 Atlas Centaur Space Shuttle

2.3 TDRS CONFIGURATION SUMMARY

The four final TDRS configurations developed are:

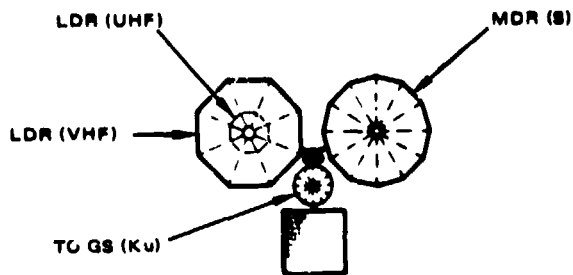
- 1) Delta 2914 launched TDRS configuration 1 (TDRS 1D)
- 2) Atlas Centaur launched TDRS configuration (TDRS AC)
- 3) Space Shuttle launched TDRS configuration (TDRS SS)
- 4) Delta 2914 launched TDRS configuration 2 (TDRS 2D)

The TDRS 1D was developed during Part I of the study, whereas the remaining configurations were developed during Part II of the study. Significantly different user service requirements were stipulated for Part II of the study which impacted directly on the antenna, electronic and power requirements, and indirectly on all spacecraft subsystems. The changes that are visible in the configuration drawings are the addition of an adaptive ground implemented phased array (AGIPA) for the LDR service, and additional MDR/HDR links, each of which require an independent antenna. These configurations are depicted in Figure 2. For clarity, some of the smaller antennas, such as order wire, backup TT&C, and ground station to TDRS receive are omitted from the figure.

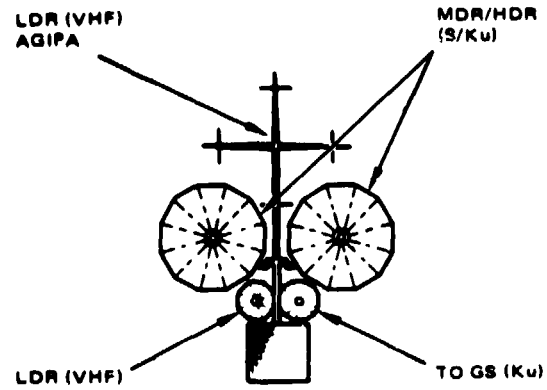
For both Delta configurations the antennas can be deployed from one despun platform. For the TDRS AC and TDRS SS the resulting antenna requirements are significant, and spacecraft dynamic studies have shown that to prevent excessive solar torque effects (frequency of attitude correction maneuvers), a reasonably symmetrical antenna placement is mandatory.

The Space Shuttle configuration design is relatively straight-forward; both end platforms are despun and the Space Shuttle payload bay diameter permits the TDRS antennas to be folded along the sides of the spacecraft; thus, both ends of the spacecraft are available for antenna mounting and deployment.

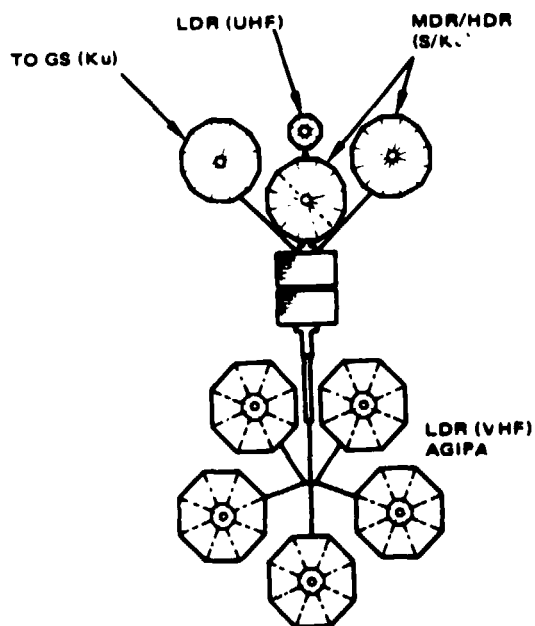
For the Atlas Centaur configuration, such a solution is not compatible with the payload fairing envelope and all antennas must be mounted to one end of the spacecraft from which the AGIPA is deployed with an extendable mast down past the rotating cylinder to the position shown in Figure 2. Such an antenna deployment is not caused by the use of the Intelsat IV bus (adapted with the objective of providing a low cost design) but would apply to any Atlas Centaur launched dual spin TDRS configuration.



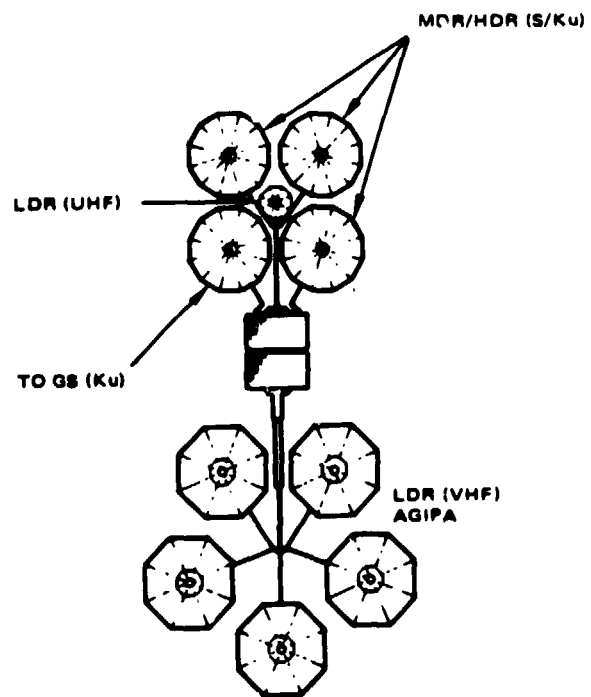
DELTA 2914 LAUNCHED
CONFIGURATION (1)



DELTA 2914 LAUNCHED
CONFIGURATION (2)



ATLAS-CENTAUR
LAUNCHED CONFIGURATION



SPACE SHUTTLE
LAUNCHED CONFIGURATION

Figure 2. TDRS Configurations

2.4 TELECOMMUNICATIONS SERVICE SUMMARY

A summary of the telecommunications service available with the various TDRS configurations is shown in Table 3. In all cases the dBW values given for the forward links are the EIRPs which were selected, within the TDRS power and mass limitations, to minimize the user impact in terms of its receiving antenna size. For the MDR users an EIRP of 47 dBW was required to meet the current Space Shuttle requirements.

The percentages given in Table 3 show the available duty cycles per orbit. During an eclipse the same duty cycle applies to the eclipse period itself.

The essential changes between the Part I and Part II configurations are:

- LDR - Addition of AGIPA; deletion of one forward channel for TDRS AC and TDRS 2D configurations
- MDR - Addition of at least one more channel
- HDR - All new
- Reduced ground link weather margins for TDRS 2D

The MDR and HDR service is supported with 3.82 meter parabolic antennas with S/Ku band feeds. The repeater electronics are independent; thus, simultaneous links with MDR and HDR users can be maintained if they are within the antenna beam; otherwise, each antenna can serve only one MDR or HDR user at a time. For HDR user service autotracking is provided. Order wire service is provided in all configurations.

The LDR service is provided over a 30 degree field of view; i. e., up to 5000 km user altitudes. Up to 20 users can be accommodated simultaneously using a broadbeam UHF antenna for transmission, and in Part II a multiple-element AGIPA array for reception.

TABLE 3. TELECOMMUNICATIONS SERVICE SUMMARY

Service	Configuration	Part I Configuration	Part II Configurations		
		TDRS 1D	TDRS AC	TDRS SS	TDRS 2D
LDR	Forward (UHF)	2 links 30 dBW (1) Continuous (1) 25% Use	1 link 30 dBW continuous	2 links 30 dBW continuous	1 link 28.5 dBW continuous
	Return (VHF)	20 users simultaneously	20 users simultaneously AGIPA for added RFI suspension		
MDR* (S Band)	Forward	1 link 47 dBW 50% use or 41 dBW continuous	2 links (1) 47 dBW 50% use or 41 dBW continuous (1) 41 dBW continuous	3 links (1) 47 dBW continuous (2) 41 dBW continuous	2 links (1) 47 dBW 25% use or 41 dBW continuous (1) 41 dBW continuous
	Return	1 link 1 Mbps continuous	2 links each up to 1 Mbps continuous	3 links each up to 1 Mbps continuous	2 links each up to 1 Mbps continuous
HDR* (Ku Band)	Forward	None	1 link 59 or 51 dBW continuous	2 links 59 or 51 dBW continuous	1 link 40 dBW continuous
	Return		1 link up to 100 Mbps continuous	2 links up to 100 Mbps continuous	1 link up to 100 Mbps continuous

* The MDR and HDR services have independent electronics but share antennas; thus the available links at any instant are defined by antenna availability.

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3. TDRSS OPERATIONS AND CONTROL

The TDRSS operations and control involve three major functions:

- TDRS launch and orbital deployment
- TDRS on-orbit control
- TDRSS telecommunication service operations

Each of these topics will be discussed briefly in the following subsections.

3.1 TDRS ORBIT INSERTION PROFILE

For TDRS 1D, TDRS AC, and TDRS 2D the TDRS launch and orbit insertion sequence is essentially similar to that used for other synchronous satellites; e.g., Intelsat IV. The only exception occurs in the Space Shuttle launch, in which case all three TDR satellites are injected into a low altitude, circular orbit with one Space Shuttle flight, following which, all three TDRSs are injected simultaneously into a synchronous transfer orbit with the Transtage. After the transfer orbit injection the TDR spacecraft are separated from the Transtage and their remaining mission profile is alike to the Intelsat IV.

During the transfer orbit, the TDRS telemetry and command will be accomplished with the S band backup telemetry, tracking, and command (TT&C) system. The satellites will be reoriented in the apogee motor firing attitude prior to the second apogee. Depending on the launch dispersions, an appropriate apogee will be selected for the apogee motor firing to achieve a favorable drift toward station after apogee injection.

At the final station orbit, trim maneuvers to circularize and synchronize the orbit will be performed. The antenna deployment will be performed at the final station after the orbit trim maneuvers are completed.

The final orbit inclinations are selected as a compromise between spacecraft mass, inclination biasing requirements, and user coverage as follows:

TDRS 1D	7 degrees
TDRS AC	3 degrees
TDRS SS	3 degrees
TDRS 2D	7 degrees

3.2 TDRS ON-ORBIT CONTROL

A TDRS can be commanded via two different on-board systems. The primary system uses Ku band and the TDRS commands are transmitted to the TDRS along with all the forward link signals to be relayed to user spacecraft. The backup system uses S band on the TDRS SS, AC, and 2D and VHF on the TDRS 1D. Omnidirectional antennas are provided for the backup TT&C.

TDRS tracking is accomplished using the LDR forward link. A signal is continuously sent to each TDRS on this link via the Ku band system. A low gain UHF antenna can be used to receive these signals at the ground station, where they are processed to provide range and range rate measurements for the TDRS.

Additional tracking capability is available with the on-board S band ranging transponder which allows trilateration measurements from ground stations.

The on-orbit control operations for the TDRS are:

- East-west stationkeeping
- Attitude maneuvers
- S band and Ku band antenna pointing
- TDRS repeater channel settings

The frequency of east-west stationkeeping maneuvers is approximately one maneuver every 100 days and the frequency of the attitude maneuvers is one maneuver every 2 days. The satellite has sufficient angular momentum so that antenna pointing will not require any real time attitude compensation. The stationkeeping and attitude correction maneuvers do not require an interruption of the telecommunication service to the users.

3.3 TDRS TELECOMMUNICATIONS SERVICE OPERATIONS

The TDRS system consists of five major elements: 1) GSFC communications control and processing facility, referred to as GSFC, 2) user and TDR spacecraft control centers, 3) ground station, 4) tracking and data relay satellites, and 5) user spacecraft. The overall functional relationship among these elements is shown in Figure 3. Figure 4 illustrates how the TDRSS augments the current ground network and employs much of the existing scheduling, switching, and data processing capability of GSFC.

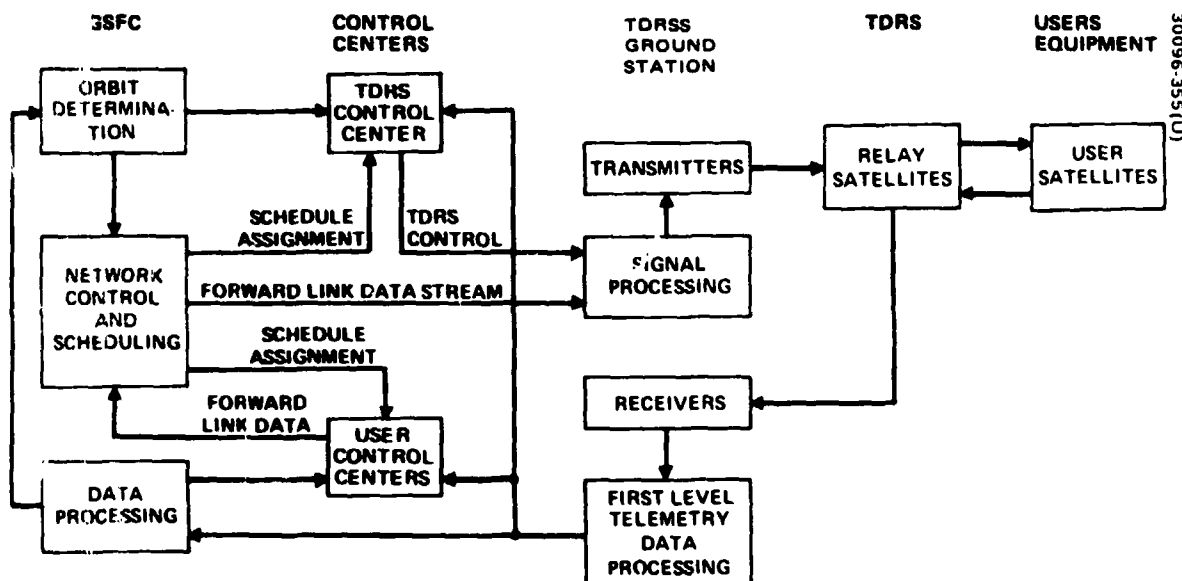


Figure 3. TDRSS Functional Operations

3.3.1 GSFC Functions

GSFC has the responsibility for scheduling the TDRSS communications services and providing most data processing. The TDRSS link availability will be defined by Network Scheduling and Control similar to the present NASA ground station scheduling and will be forwarded to the users on a regular schedule. The schedule provided to the users and the TDRS control center will include the times that communication will be enabled and the relay satellite through which this communication will occur. As is the case with the present ground network, all groups involved will regulate their activities in accordance with these schedules. The various users will transmit their commands to a command processing operation at GSFC, which will assemble the forward link data stream in accordance with user requests, service capability, and priority assignments. During the scheduled times this data stream will be forwarded to the TDRSS ground station for transmission to the user satellites.

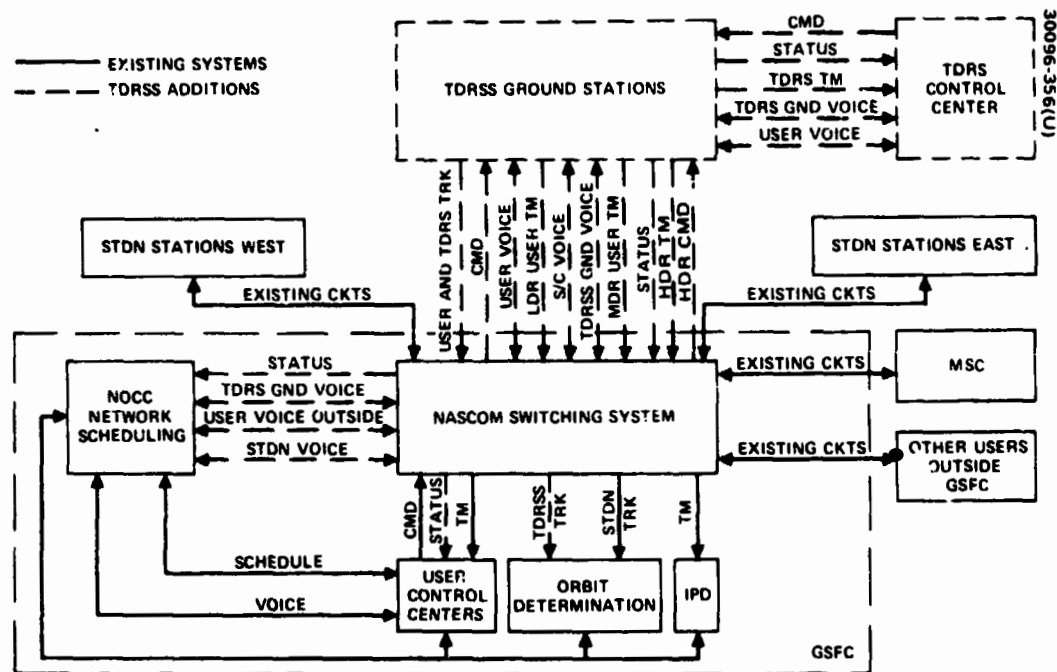


Figure 4. TDRS Ground Network

3.3.2 TDRS Control Center

The TDRS control center (TDRS CC) originates commands for the TDR satellites and forwards them to the ground station for transmission to the TDR satellites. These commands configure the repeater and point the steerable antennas, as well as produce housekeeping and subsystem control functions.

3.3.3 TDRSS Ground Station

The TDRSS ground station (TDRSS GS) is the interface between the TDRS CC, GSFC, and the TDR satellites. All modulation/demodulation, multiplexing/demultiplexing, and RF transmitting/receiving is performed at this facility.

Telemetry data after a first level decommutation at the TDRSS GS will be transmitted to the existing data processing facility at GSFC. As is the case with the present ground network, the processed data will be sent to the appropriate users, with TDRS data going to the TDRS CC. Orbit determination for both the TDRS and user satellites is performed at GSFC and made available to the user program offices and to the TDRS CC which is responsible for TDRS control.

3.3.4 TDR Satellites

The TDRS is, operationally, the simplest of all the elements in that it acts only as a "bent pipe" that relays the signals received from the ground station to the user and relays the user signals to the ground station. The appropriate channel settings for MDR users and the required antenna pointing will be commanded from the TDRS CC.

3.3.5 User Telecommunications Terminal

The users equipment will, in principle, operate similarly to the TT&C equipment in present satellites. The unique aspects are the PN coding for the LDR and MDR users and the acquisition and autotracking for HDR users. The operational procedures for all users are discussed in subsection 3.4.

3.4 USER SERVICE PROFILES

To provide an understanding of the operational steps involved in establishing a link of each of the services, brief descriptions of the procedures are given below.

3.4.1 LDR Service Profile

A typical sequence for LDR service to a user spacecraft is illustrated in Figure 5. Position 1 represents the end of an occultation period during which TDRS E was not visible to the user spacecraft. The user receiver is set to the TDRS E code, and is automatically synchronized to the signal transmitted from TDRS E. Following this signal acquisition (estimated less than 60 seconds), the user spacecraft is ready to receive commands. If the user is transmitting, ground receivers corresponding to that user's coded telemetry signal will acquire the user's signal in less than 60 seconds, after which range and range rate measurements may be made simultaneously with telemetry data reception.

In position 2 the user is visible to both TDR spacecraft, and a command is sent to the user via TDRS E to change his receiver code to correspond to the signal from TDRS W. This change is followed by automatic acquisition of the signal from TDRS W, position 3. Finally, in position 4 before occultation, the user is commanded to change his receiver code back to TDRS E in preparation for communication following occultation. Note that only two receiver codes are required for all users.

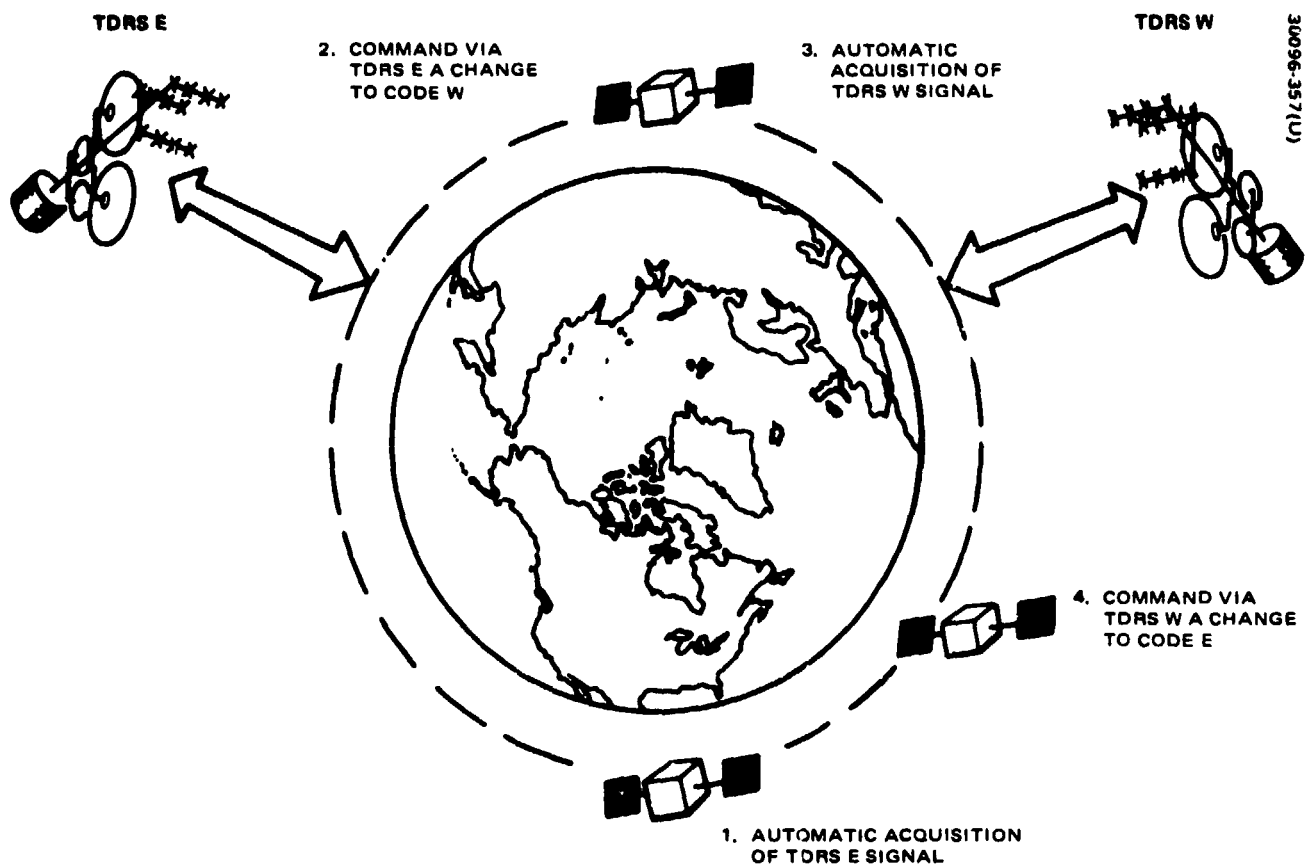


Figure 5. Low Data Rate Service Profile

3.4.2 MDR Service Profile

The operational sequence of events for establishing an MDR service two-way link with a user is more straightforward than for the LDR service because only one user per TDRS is accommodated at a time. Antenna pointing and TDRS repeater frequency translation characteristics to allow communications are established in the following sequence:

- Scheduled service or priority override by S band order wire
- Set TDRS receiver and transmitter channel frequencies
- Point TDRS S band antenna at user by ground command
- Acquire signal and begin two way communications

3.4.3 HDR Service Profile

In addition to signal synchronization, a major consideration for the HDR links is the antenna beam acquisition and autotracking. The antenna half-power beamwidth will be less than 0.5 degree for most HDR users, necessitating special equipment for rapidly establishing the HDR user/TDRS link. The basic equipment required is as follows:

- 1) S band receiver with an omnidirectional antenna
- 2) Steerable, dual gain Ku band antenna
 - Low gain - transmit only
 - High gain with a tracking feed - transmit and receive

The dual gain antenna should probably consist of two separate antennas and feeds rigidly connected to each other with parallel boresights. Only the high gain antenna needs a tracking feed. With this equipment the acquisition sequence is as follows:

- 1) The TDRS is commanded to point its S/Ku band antenna at the user (possible to at least ± 1.0 degree accuracy) and an unmodulated carrier is transmitted at Ku band.
- 2) The TDRS transmits the following commands at S band which are received, verified, and executed via the users S band receiver with the omnidirectional antenna:
 - Point antenna at TDRS (possible to at least ± 3 degree accuracy)
 - Switch Ku band power amplifier output to low gain antenna
 - Turn off carrier modulator
 - Turn on transmitter
- 3) The TDRS performs a spatial scan and acquires the user carrier
- 4) The user is commanded via S band to perform a scan acquisition of the TDRS signal
- 5) Following acquisition, the autotrack system is automatically activated, the user switches its transmitter to the high gain antenna, and data transmission begins.

The maximum time required to perform steps 3 through 5 above is estimated to be 45 seconds. The time required for the antenna slewing of steps 1 and 2 will depend on the user's position and the user's antenna slew rates. For instance, with the TDRS antenna slew rate of approximately 1 degree per second, slewing across the earth disc will require approximately 20 seconds. The user may be required to slew as much as 180 degrees, which would take 120 to 240 seconds depending on its positioner capability. The latter delay could be eliminated by prepositioning the antenna for the next communication period after each transmission.

4. TELECOMMUNICATION SERVICES

The telecommunications service levels provided by the TDRSS are summarized in this section. The service level is identified by the bit rate which can be transmitted to or from a user spacecraft via a TDRS. In the following subsections the LDR, MDR, and HDR service bit rates are shown graphically as a function of the pertinent system parameters. The performance level of all configurations is shown in each figure.

The MDR and HDR service is implemented with dual feed (S and Ku band) antennas. S band is allocated for MDR and Ku band is allocated for HDR service. Due to this implementation, time sharing between the MDR and services will likely be required for any planned use of the various links. Although normally this will not be a restriction, the availability of sufficient power from the electric power subsystem should be verified from Table 15.

4.1 USER SYSTEM VISIBILITY BY TDRSS

User visibility by the TDRSS is shown in Figure 6. The ordinate of the figure represents a ratio of the area visible to two TDRSs to the total surface area of a sphere at the user altitude. Such a ratio will usually not represent the user visibility during any single orbit; however, it is a good quantitative characterization of the average user visibility.

Note that for orbital altitudes above 5000 km a user will be outside the TDRS antenna coverage pattern (30 degree cone) part of the time, and user visibility will decrease with increases in orbital altitude above this limit.

4.2 LOW DATA RATE (LDR) SERVICE

The LDR links between a TDRS and user spacecraft employ broad coverage antennas, accommodating user spacecraft with orbital altitudes up to 5000 km. All TDRS configurations employ a single UHF short backfire antenna for the forward link. The return link is implemented with a single VHF backfire antenna for the TDRS 1D and with adaptive ground implemented phased arrays (AGIPA) for the TDRS AC, TDRSSS, and TDRS 2D.

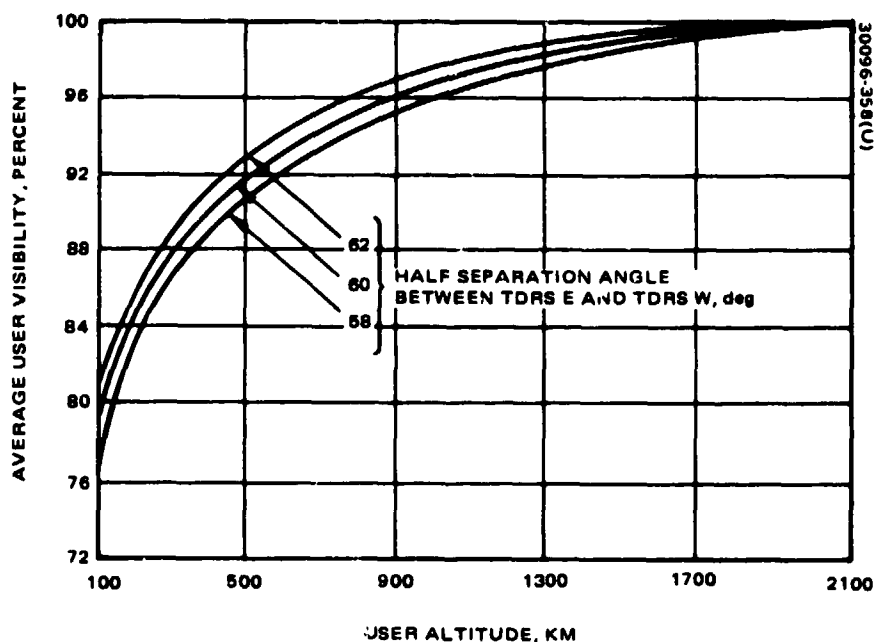


Figure 6. User Visibility by TDRS

The design of the LDR service and signal processing allows communication with a minimum of 20 users per TDRS for both the forward and return links.

The use of PN coding is the major signal design characteristic and allows four objectives to be accomplished: 1) multipath interference is reduced due to the spectrum spreading, 2) earth-incident flux density is reduced to meet CCIR requirements, 3) range measurement accuracy is improved, and 4) code division multiplexing for the return link is provided.

Both forward and return links are affected by RFI. The geometry associated with RFI is illustrated in Figure 7. Each TDRS sees more than 40 percent of the earth's surface, and the LDR return link antenna collects noise power from emitters in the visible region. The total RFI noise level visible to each TDRS will vary slowly, since each TDRS always views the same large region. A low altitude user spacecraft views a considerably smaller portion of the earth's surface, and therefore is affected by a lesser number of RFI emitters but is much closer to these emitters, effectively receiving high power from each emitter than the TDRS. A user, orbiting over high and low RFI emitting regions, experiences a wide range of RFI variations.

The bit rate capacities of both the LDR forward and return links are limited by RFI. Since the level of this interference has not been reliably determined to date, in the subsequent figures the bit rate capacity of these links is represented as a function of the total RFI level.

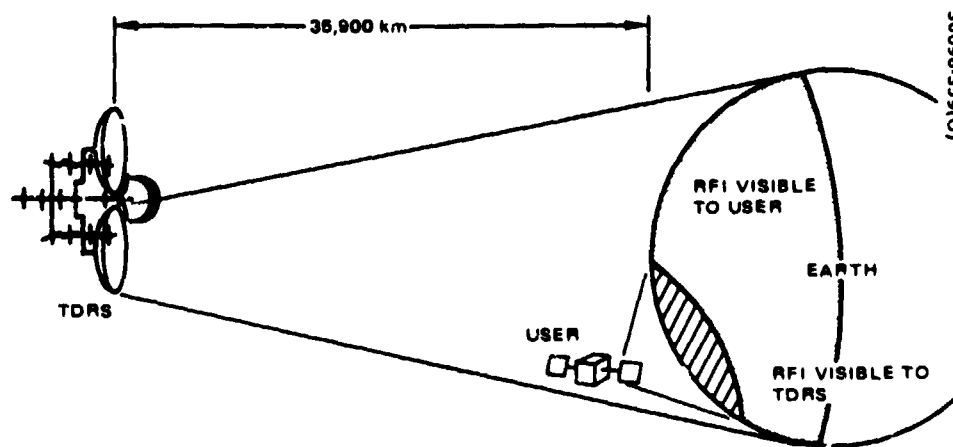


Figure 7. RFI Geometry

4.2.1 Forward Link

The forward links are time-shared; i.e., only one user can be commanded at a time per TDRS forward link. Furthermore, synchronized sequencing of user commands is required. However, there is no system limit to the number of users to which commands can be sent, since each command will have a user identifying prefix that activates the command decoder of the intended user. Other link features include: automatic user acquisition, variable user command format, and fixed timing. The fixed timing permits standardization of user receivers and simplifies ground station operations and equipment.

The frequency band chosen is the UHF band 400.5 to 401.5 MHz. This band was selected over a VHF band because: 1) more bandwidth is available, 2) RFI is expected to be smaller, and 3) it is a currently internationally allocated band for space use. Although the signal parameters selected will depend on the RFI level and desired link margins, a preliminary baseline set is given below:

- | | |
|-------------------------------|-------------------|
| 1) Command bit rate | 300 bps |
| 2) PN code length | 2048 |
| 3) Chip (PN code symbol) rate | 614 kchips/second |
| 4) Voice bit rate* | 9.6 kbps |

*TDRS 1 and TDRS SS only

The TDRS 1D and TDRS SS provide two forward links, while the TDRS AC and TDRS 2D provide one. On the TDRS 1D one forward link is restricted to 25 percent usage due to power limitations. Both links are unrestricted on the TDRS SS.

Figure 8 shows the maximum bit rate as a function of the RFI power density. The TDRS 2D has approximately 1 dB less transmitter power; thus an EIRP of 30 dBW can be obtained only over a 19.7 degree FOV (equivalent to 1000 km user altitudes). However, the EIRP over a 30 degree FOV is only slightly degraded, namely, 28.5 dBW.

The RFI effects dominate over the multipath and the thermal noise effects and result in the linear relationship on the right side of the figure, while at low RFI levels the thermal noise and multipath cause the asymptotic behavior on the left side of the figure.

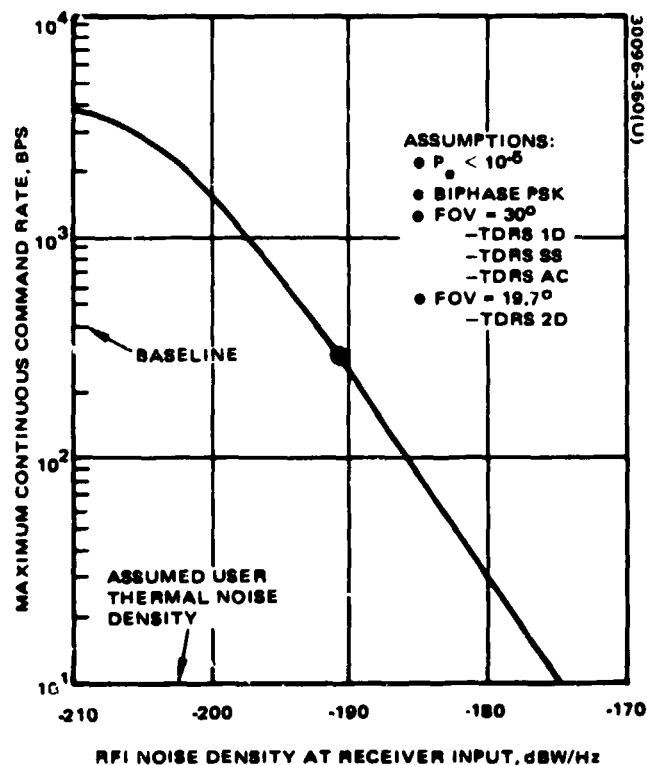


Figure 8. Low Data Rate Forward Link

4.2.2 Return Link

The LDR return link allows simultaneous telemetry reception from up to 20 users per TDRS. The frequency band is 136 to 137 MHz.

The selected signaling and multiplexing techniques are as follows:

- 1) User telemetry will be PN code modulated to occupy the entire 1 MHz band
- 2) Simultaneous multiple user telemetry signals are code division multiplexed in the 136 to 137 MHz band; thus, each user's PN code will be different
- 3) Convolutional encoding will be employed on user telemetry for bit error correction; link quality is improved significantly with this technique.

The baseline approach assumes that the return bit rate is standardized for all users (this is not a system requirement). Using this assumption, the baseline parameters are as follows:

- | | |
|--------------------------------|--------------------|
| 1) Telemetry bit rate | 1200 bps |
| 2) Convolutional encoding rate | 1/2 |
| 3) PN code length | 511 |
| 4) Chip rate | 1.22 Mchips/second |

The return link performance as a function of RFI is shown in Figure 9. Performance curves are shown for all four TDRS configurations. The AGIPA performance curves were obtained with a Hughes computer simulation using the AIL RFI model of October 1972.

The AGIPA antennas on the TDRS AC, TDRS SS, and TDRS 2D configurations allow spatial discrimination against RFI. The figure indicates that the AGIPA antennas provide a considerable improvement over the data rate capability with a single aperture antenna. At high RFI levels the five element AGIPA shows higher performance than the four element AGIPA. However, this is much smaller improvement than that of the four element AGIPA over the single aperture antenna. The five element AGIPA will provide a large improvement over the four element AGIPA if the RFI level is low, but in this case the four element AGIPA, and possibly even the single aperture antenna, may be adequate, providing data rates greater than 1 kbps. The results shown in the figure indicate that the four element AGIPA provides a highly adequate performance level.

The ranges of performance shown for each TDRS configuration are due to the fact that RFI suppression depends on the position of the user spacecraft with respect to the spatial distribution of the RFI sources.

Similar to the forward link, the asymptotic behavior of the curves on the left side of the figure is due to thermal noise and multipath plus cross-correlation noise. The linear behavior on the right side of the figure is due to the dominance of the RFI over these other noise sources.

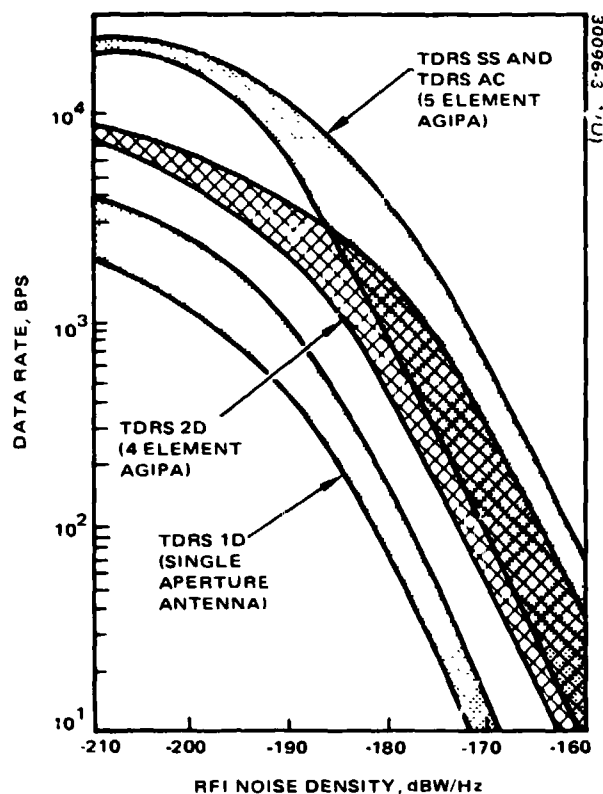


Figure 9. Low Data Rate Return Link

4.2.3 User Tracking

Tracking refers to range and range rate measurements from which user orbital parameters can be derived. The geometry depicted in Figure 10 shows the four segments that are involved in the required two-way transmission. Thus, four transmitters and four receivers are active in this process; two of each are on the TDRS.

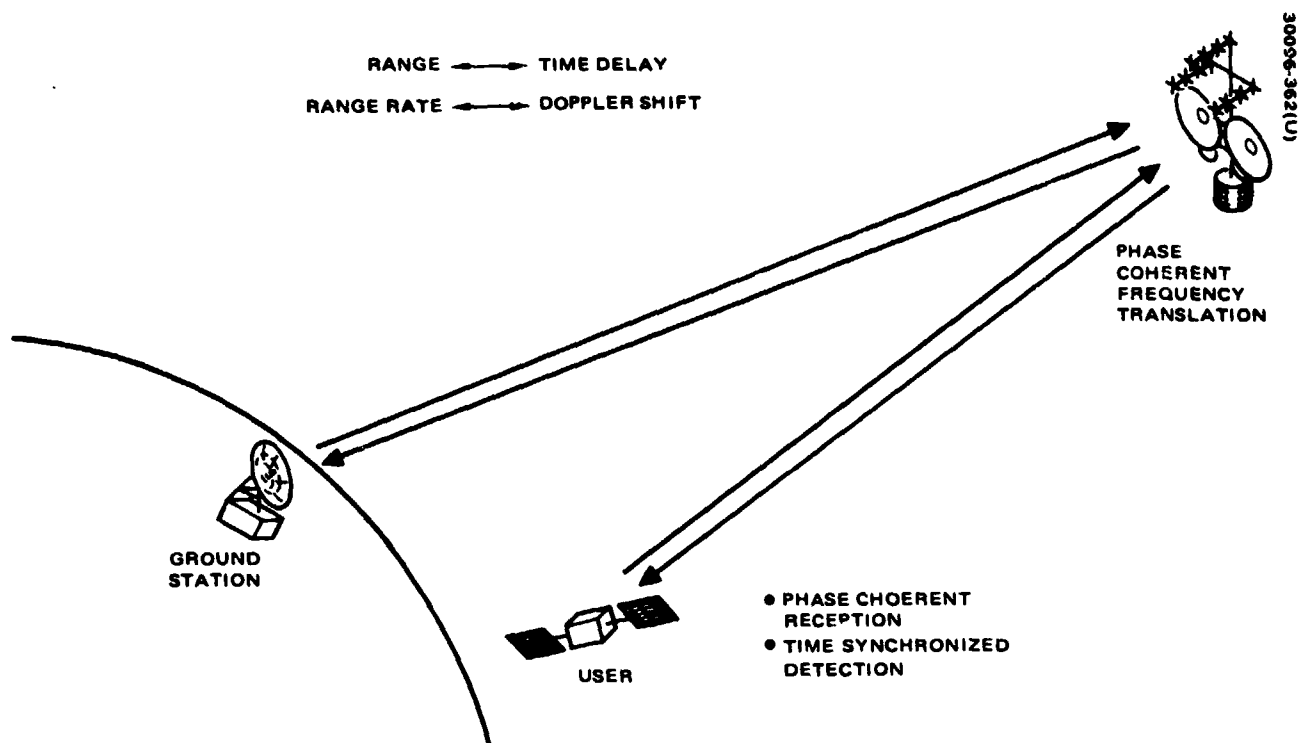


Figure 10. User Tracking

Range rate measurement requires the determination of total doppler shift at the ground station, and thus requires phase coherence of the three oscillators in the respective terminals as shown. Measurement of range requires time delay determination in the round trip signal transmission; thus, timing synchronization is required. The use of PN codes in the low data rate services automatically provides this synchronization at both user and ground station.

A particular operational advantage of the signaling concepts used here is that since the user spacecraft receivers automatically acquire and synchronize to the signal transmitted from a TDRS, both range and range measurements can be made simultaneous with telemetry reception, and no forward link commands are required.

Figure 11 shows the estimate of the rms range measurement uncertainty in the forward and return links as a function of RFI noise density for the TDRS SS, AC, and 2D configurations employing the AGIPA. The total rms uncertainty is the sum of the two.

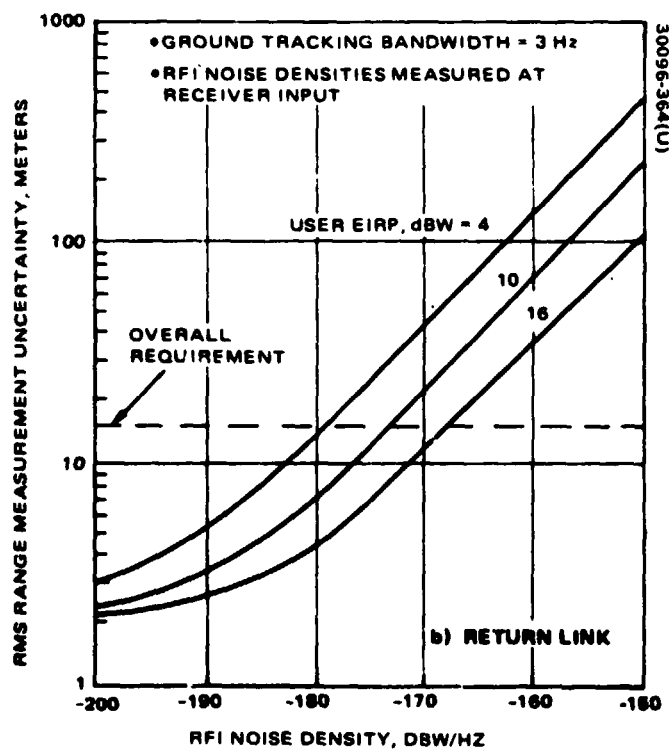
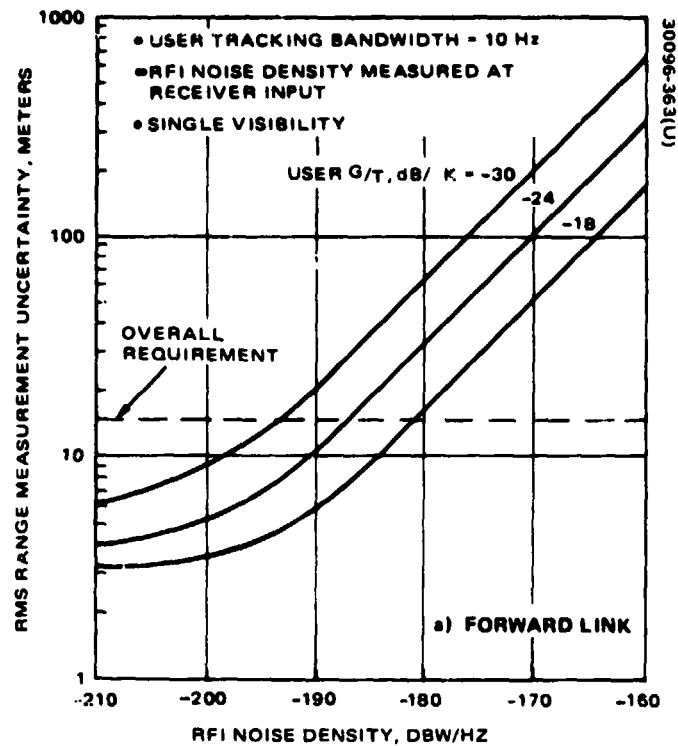


Figure 11. RMS Range Measurement Uncertainty

4.3 MEDIUM DATA RATE (MDR) SERVICE

The MDR service requires high gain antennas on each TDRS. These antennas have the angular freedom to follow user spacecraft in orbit with altitudes up to 5000 km. Because of the narrowbeam antenna pattern, two-way communication is possible with only one user spacecraft at a time via each antenna.

For every configuration the TDRS repeater has been designed to accommodate a 1 Mbps data rate on each return link. The S band transmitters operate at two power levels, providing two EIRP levels: 47 and 41 dBW.

The wideband phase coherent repeater allows range and range rate measurements to be made by almost any method preferred by the user. In addition, capability is provided to position the transmit (forward link) 30 MHz band, anywhere in the 2038 to 2118 MHz frequency range and to position the receiver (return link) 10 MHz band anywhere in the 2200 to 2300 MHz range.

The TDRS 1D has only one MDR link, the TDRS AC and TDRS 2D each have two, and the TDRS SS has three.

4.3.1 Forward Link Calculations and Parameters

The forward link data rate is based on the following link equation:

$$\begin{aligned} \text{Bit rate (R}_b\text{)} = & \text{User antenna gain (G}_u\text{)} + \text{TDRS EIRP} \\ & - \text{Space loss (L}_s\text{)} \\ & - \text{Pointing and ellipticity losses (L}_p\text{)} \\ & - \text{Receive losses (L}_r\text{)} - \text{Boltzmann's constant (C}_F\text{)} \\ & - \text{Receiving system noise temperature (T}_s\text{)} \\ & - \text{Required bit energy-to-noise density (E}_b/\eta\text{)} \\ & - \text{Link margin (M)} \end{aligned}$$

where each term is expressed in decibel units. Table 4 lists the values of the above parameters. Note that the Space Shuttle service includes a higher quality receiver (T_s), coding (E_b/η) and a link margin (M).

TABLE 4. MDR FORWARD LINK PARAMETERS, dB

Parameter	MDR User Service, TDRS EIRP, 41 dBW	Space Shuttle Service, TDRS EIRP, 47 dBW
L_s	-192.0	-191.3
L_p	-2.0	-1.0
L_r	-2.0	-3.0
C_B	228.6	228.6
T_s	-29.0 (800K)	-27.3 (540K)
E_b/η	-10.0	-4.4 (with coding)
M	0.0	-3.0
Total	-6.4	-1.4
R_b	$G_u + \text{EIRP} - 6.4$	$G_u + \text{EIRP} - 1.4$

4.3.2 Forward Link Performance

Each MDR forward link is identical on all configurations, the differences between the configurations are the number of links provided (summarized in Table 3). Figure 12 relates the maximum data rate to the user antenna gain for a TDRS EIRP of 41 dBW, which is planned for unmanned MDR users. The assumptions for the performance calculations are contained in section 4.3.1.

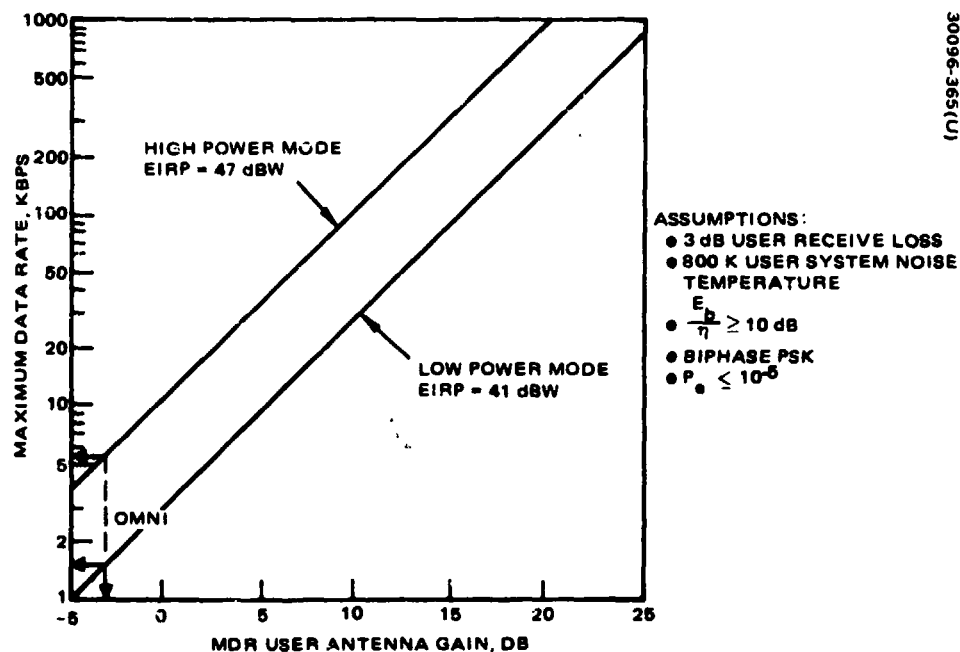


Figure 12. Medium Data Rate Forward Link

The available forward link service to the Space Shuttle is shown parametrically in Figure 13. Time division multiplexed digital signals at a rate of 54 kbps (comprised of two delta-modulated voice signals at 24 kbps and 6 kbps of encoded data) can be accommodated with the currently planned 3 dB gain Space Shuttle antenna. The assumptions used in deriving the figure (summarized in section 4.3.1) are consistent with current GSFC/ MSC specifications.

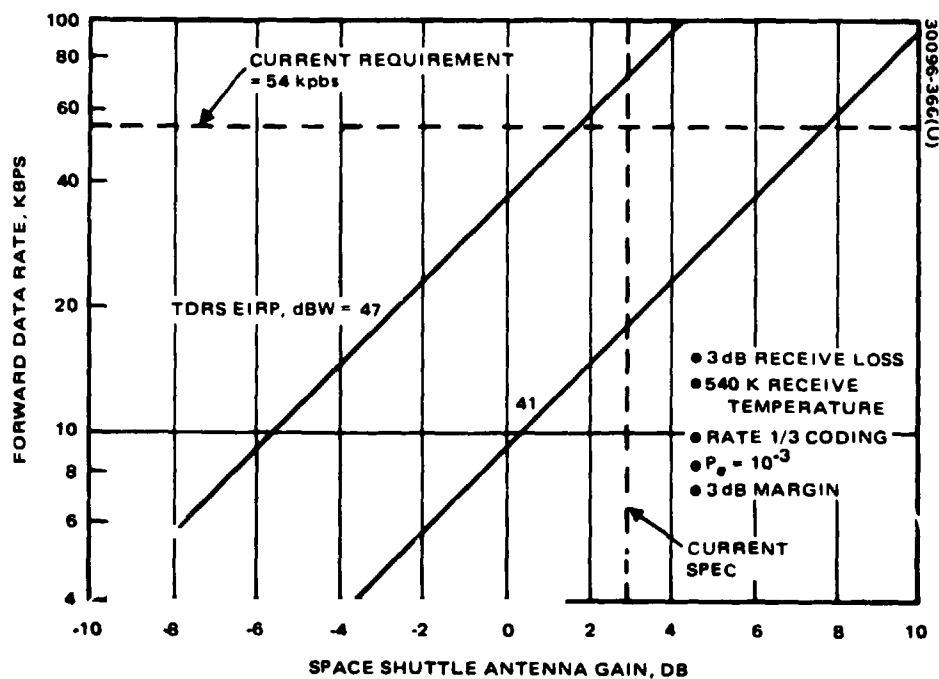


Figure 13. Space Shuttle Service Forward Link

4.3.3 Return Link Calculations and Parameters

The return link data rate is based on the following link equation:

$$\begin{aligned} \text{Bit Rate } (R_b) = & \text{User antenna gain } (G_u) + \text{User radiated } (P_{RF}) \\ & + \text{TDRS antenna gain } (G) - \text{Space loss } (L_s) \\ & - \text{Pointing and ellipticity losses } (L_p) \\ & - \text{Receive line losses } (L_r) - \text{Boltzmann's Constant } (C_B) \\ & - \text{Receiving system noise temperature } (T_s) \\ & - \text{Required bit energy to noise density } (E_b/\eta) \\ & - \text{Margin } (M) \end{aligned}$$

where each term is in decibel units. Table 5 lists the values of the above parameters.

The term used to characterize the individual TDRS configurations is $G/L_r T_s$. The parameter values are given in Table 6.

TABLE 5. MDR RETURN LINK PARAMETERS, dB

Parameter	MDR User Service	Space Shuttle Service
P_{RF}	10.0	13.0
L_s	-192.7	-192.7
L_p	-0.5	-1.0
C_B	228.6	228.6
E_b/η	-10.0	-5.2
M	0	-2.0
Total	35.4	40.7
R_b	$G_u + G/L_r T_s + 35.4$	$G_u + G/L_r T_s + 40.7$

TABLE 6. TDRS CONFIGURATION MDR
RETURN LINK PARAMETERS, dB

Parameter	TDRS 1D	TDRS AC, TDRS SS, TDRS 2D
G	36.7	36.2
T_s	-28.6	-26.0
L_r	-2.2	-0.8
$G/L_r T_s$	5.9	9.4

4.3.4 Return Link Performance

The return link performance has been improved for Part II configurations. The link performance curves for MDR user and Space Shuttle service are shown in Figures 14 and 15, respectively. The user antenna gain is selected as the independent parameter in both figures.

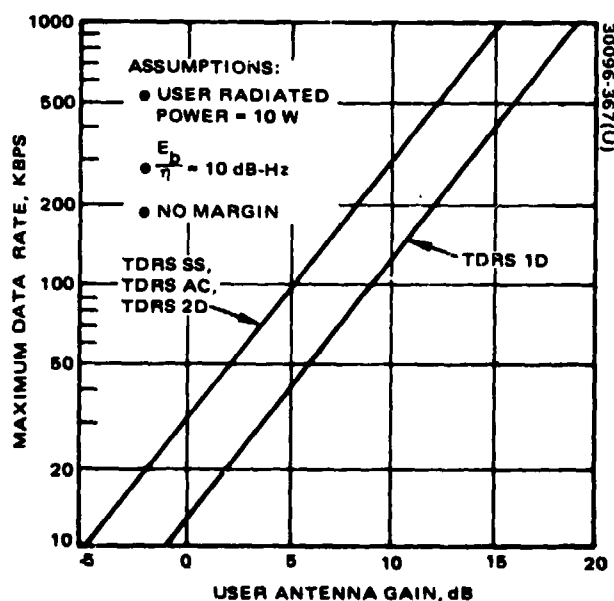


Figure 14. Medium Data Rate Return Link

For the Space Shuttle, a radiated power of 40 watts and 3 dB line losses have been assumed. Detailed assumptions for the performance calculations are contained in subsection 4.3.3.

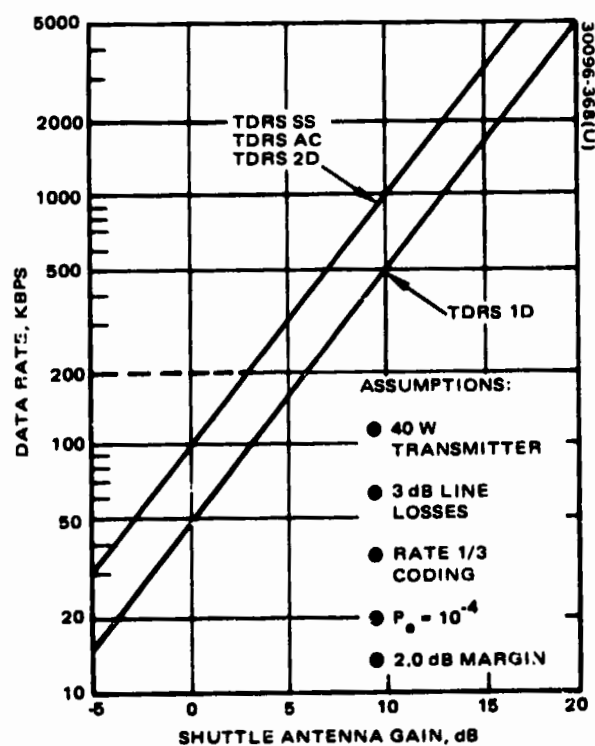


Figure 15. Space Shuttle Service Return Link

4.4 HIGH DATA RATE (HDR) SERVICE

This service is accommodated for the Part II configurations by the use of steerable reflector antennas of 3.82 meter diameter. These are the same dual feed (S and Ku band) antennas which provide MDR service, thus time sharing with the MDR service will be required. Ku band is used for the TDRS/user HDR links. High data rate service is not provided by the TDRS 1D configuration.

The various link and TDRS configuration parameters used in the link calculations are summarized in Tables 7 and 8.

TABLE 7. HDR LINK PARAMETERS, dB

Forward Link	Return Link
$L_s = -208.9$ $L_p = -1.2$ $L_r = -2.0$ $C_B = 228.6$ $T_s = -31.1$ (1280 K) $E_b/\eta = \begin{cases} -12.1 \text{ (SS and AC)} \\ -11.1 \text{ (2D)}^* \end{cases}$ $M = -0.5$	$PRF = 10$ $L_s = -208.3$ $L_p = -1.2$ $C_B = 228.6$ $E_b/\eta = -10.6^{**}$ $M = -1.0$
$Total \begin{cases} -27.2 \text{ (SS and AC)} \\ -26.2 \text{ (2D)} \end{cases}$	$Total = 17.5$
$R_b = G_u + EIRP - 26.2/27.2$	$R_b = G_u + G/L_r T_s + 17.5$

* Lower data rates

** Includes 2.5 dB demodulation degradation and 3.0 dB ground link degradation

TABLE 8. TDRS CONFIGURATION HDR RETURN LINK PARAMETERS, dB

Parameter	TDRS AC and TDRS SS	TDRS 2D
G	51.9	51.9
T_s	-28.7	-31.7
L_r	-2.0	-2.3
$G/L_r T_s$	21.2	17.9

4.4.1 Forward Link

The performance of the three configurations providing HDR service are shown in Figure 16. The TDRS AC and TDRS SS have identical transmitters capable of two power levels and their performance is equal. The TDRS 2D has a smaller transmitter with a fixed power level which results in a lower performance level.

Typically, with a 2 meter antenna, on the user, the TDRS AC and TDRS SS are capable of relaying up to 50 Mbps, which is almost twice the equivalent requirement for commercial television. The TDRS 2D with a reduced forward link capability can still relay up to 90 kbps for the same user antenna size.

The user antenna gain has been converted into reflector diameter assuming a 50 percent aperture efficiency. In the determination of the required E_b/η value, 1.5 dB was added to the theoretical requirement to account for imperfect demodulator operation when receiving from the TDRS 2D. This allowance was increased to 2.5 dB for the higher data rate TDRS AC and TDRS SS configurations.

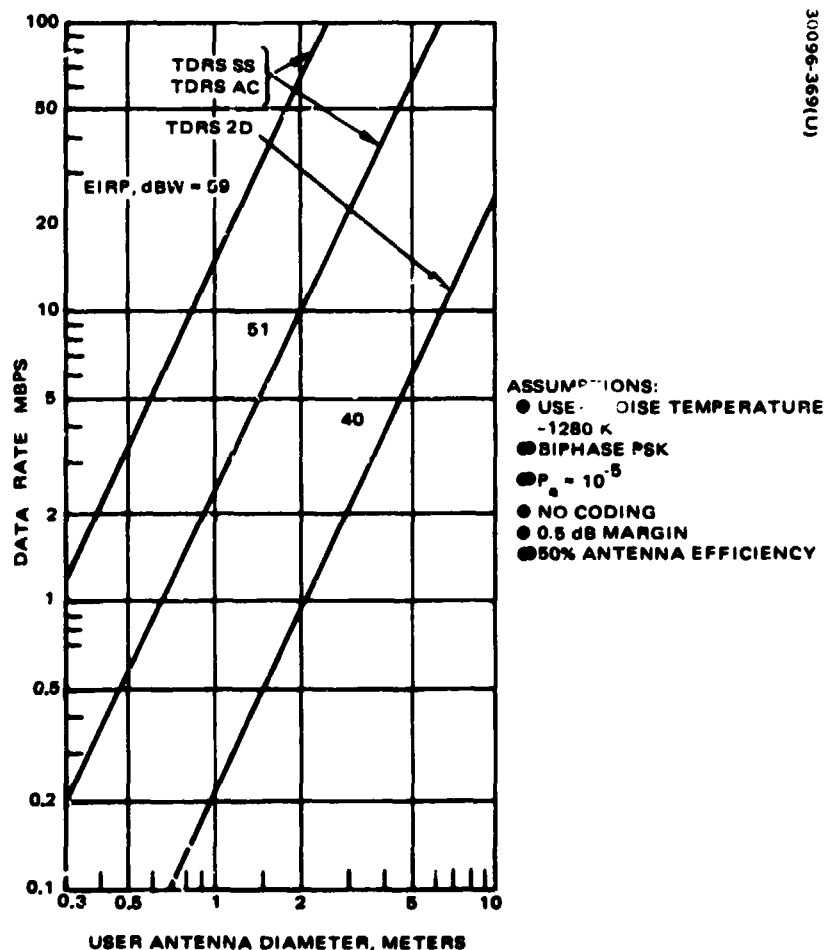


Figure 16. High Data Rate Forward Link

4.4.2 Return Link

The TDRS SS provides two HDR links, each restricted to data rates of 100 Mbps or less due to bandwidth limitations in the TDRS to ground link. The TDRS AC and TDRS 2D provide only one HDR link and the additional available bandwidth will allow data rates up to 200 Mbps.

The relative performance of the TDRS SS and TDRS AC and TDRS 2D are shown in Figure 17. These results contain the following assumptions: 1) user radiated power of 10 watts, 2) convolutional encoding for error correction, and 3) user antenna efficiency of 50 percent. It should be noted that radiated power is that which is emanated from the antenna feed and is not the same as transmitter power, which must be larger to allow for line losses. For radiated power levels of less than 10 watts, both curves in the figure will shift lower, but will maintain the same relative spacing.

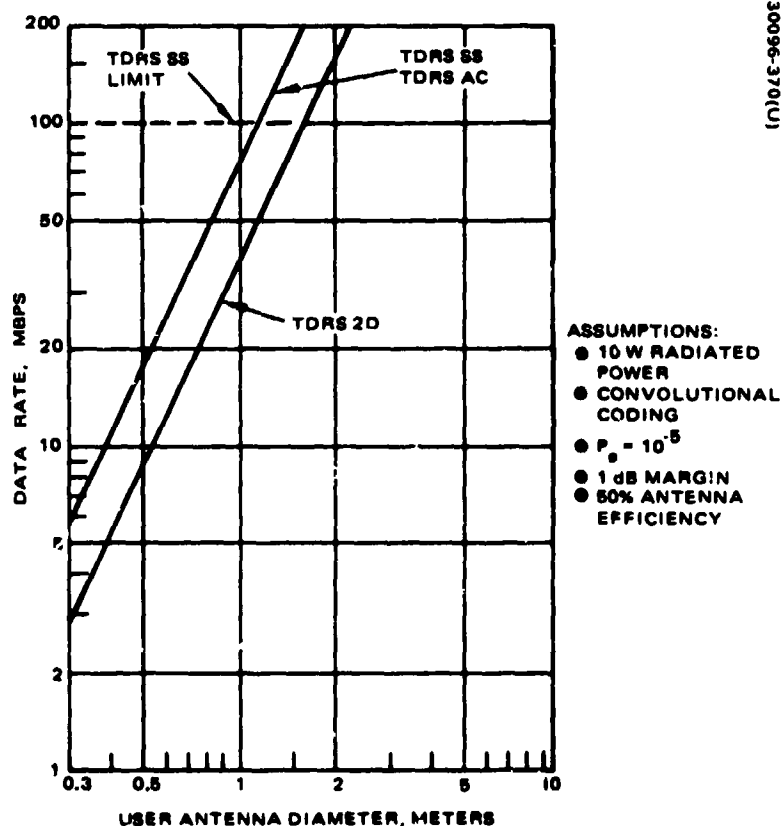


Figure 17. High Data Rate Return Link

4.5 COMPARISON OF LINK DESIGNS

In comparing the telecommunications service of the four TDRS configurations, it is appropriate to point out the link characteristics that are common to all configurations. These are shown in Table 9.

TABLE 9. TELECOMMUNICATIONS SERVICE CHARACTERISTICS
COMMON TO ALL CONFIGURATIONS

Service	Link	
	Return	Forward
LDR (VHF/UHF)	1) 20 users simultaneously 2) Code division multiplexing 3) 136 to 137 MHz	1) Single aperture short backfire antenna 2) Time shared 3) 400.5 to 401.5 MHz
MDR (S band)	1) 1 Mbps design data rate 2) Variable frequency in 2220 to 2300 MHz 3) Order wire service	1) Two EIRP levels 47 and 41 dBW 2) Variable frequency in 2038 to 2118 MHz
HDR* (Ku band)	100 Mbps design data rate	

*Not available with TDRS 1C

The LDR forward link employs the UHF band while the return link uses the VHF band. A single aperture UHF antenna is used. Twenty LDR users signals may be returned simultaneously via each TDRS.

The MDR service employs S band frequencies. All configurations employ forward link transmitters with two selectable power levels, and the return links are designed for 1 Mbps. A 10 MHz channel for both forward and return links may be chosen anywhere in the respective bands of approximately 80 MHz. In addition, an order wire service is provided which allows a manned spacecraft to request the MDR service.

HDR service is provided only by TDRS AC, TDRS SS, and TDRS 2D. Ku band was selected over X band for this service because of the lesser impact on the user.

Table 10 lists those major parameters related to each service which differ between configurations. The details on the relative performances of the links has been treated in the previous sections.

The EIRP includes transmitter power, antenna gain, and line losses. G/LT includes the effect of antenna gain, line losses, and all receiving system noise. The larger the number in any row, the better the performance or greater the capability.

TABLE 10. TELECOMMUNICATIONS SERVICE CHARACTERISTICS

Service Characteristic			Launch Vehicle			
			Part I	Part III		
			TDRS 1D	TDRS AC	TDRS SS	TDRS 2D
LDR	Forward	Number of Links	2	1	1	1
		EIRP, dBW	30	30	30	29
	Return link antenna		Single antenna	5 element AGIPA		4 element AGIPA
MDR	Number of two-way links		1	2	3	2
	Return G/LT, dB/K		5.9	9.4	9.4	9.4
HDR	Number of two-way links		0	1	2	1
	Forward EIRP, dBW		—	59/51	59/51	40
	Return G/LT, dB/K		—	21.2	21.2	17.9

The TDRSS SS provides the highest level of service, while the TDRS 2D provides the minimum adequate level of services. The TDRS AC is a mixture of the two. The TDRS 1D provides the highest grade LDR forward link, (as does the TDRS SS), but is poorer in LDR return, MDR return, has less MDR links and provides no HDR service at all.

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5. TELECOMMUNICATION SERVICE SYSTEM

The TDRSS telecommunication service system consists of four major elements:

- TDRS telecommunication subsystem
- TDRSS user equipment
- TDRSS ground station
- GSFC facilities for network scheduling and control, orbit determination, and data processing.

The first three elements will be briefly discussed in the following sections, whereas the GSFC facilities will not be discussed in this report.

5.1 TDRS TELECOMMUNICATION SUBSYSTEM

The telecommunication subsystem interfaces with the ground station at Ku band and with the users in the VHF/UHF bands, S band and Ku band. UHF and VHF are used to communicate with LDR users, S band and Ku band are used to communicate with MDR users and HDR users, respectively. The TDRS receives simultaneously several different Ku band carrier frequencies from the ground station. These carrier frequencies are shifted to a low IF, amplified, divided in a power divider and distributed to various points within the TDRS repeater.

Figure 18 illustrates in extremely simplified form the basic functions of the TDRS repeaters for all TDRS configurations. The forward LDR signal is received from the ground station via an earth coverage Ku band horn. The frequency synthesizer reference beacon and TDRS commands are also received via this antenna, but are not shown in the diagram. All return signals are transmitted to the ground station via a steerable, high gain Ku band antenna.

LDR forward link from TDRS to users employs a UHF transmitter and single aperture antenna. The return link from user spacecraft employs a VHF antenna or antenna array, depending on the TDRS configuration.

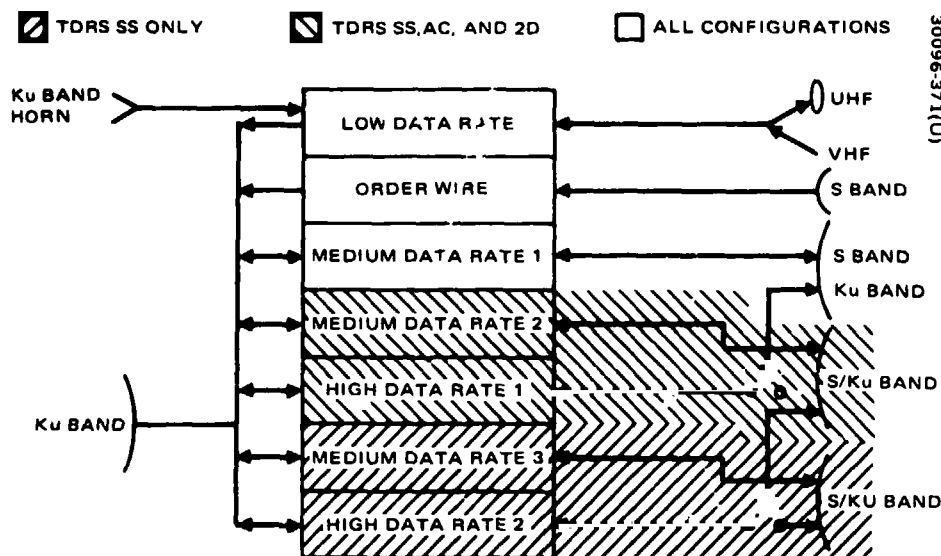


Figure 18. TDRS Repeater Functions

The order wire channel has an S band receiver and a separate small backfire antenna. The MDR links employ 3.82 meter diameter reflector antennas, and for the TDRS SS, TDRS AC, and TDRS 2D these reflectors have dual feeds (S and Ku band) and are shared with the HDR service.

The TDRS S band transmitter has a 30 MHz bandwidth tunable within the 2038 to 2118 MHz band. A single user is serviced by each S band transmitter and receiver. The receiver operates in the 2200 to 2300 MHz band. The S band receiver has a 10 MHz bandwidth, and as in the case of the transmitter may be tuned in 1 MHz steps. Thus, the S band system is capable of operating at any frequency within the assigned frequency bands and provides a "bent-pipe" system.

The TDRS SS provides all the units shown in Figure 18, while the TDRS AC and TDRS 2D have one less two-way MDR and HDR channel and one less 3.82 meter reflector. The TDRS 1D has only one 3.82 meter reflector with an S band feed; thus, it provides only one MDR channel in addition to LDR and order wire service.

Figure 19 adds more detail, but still is a simplified block diagram of the TDRS repeaters. The sum of all return MDR, LDR, order wire, and TDRS telemetry signals is amplified linearly with a Ku band TWT output stage. Linearity is achieved by operating backed off below saturation power by 5 dB or more, depending on the signal sum level. This linear amplification is required to reduce intermodulation noise and to reduce distortion in the code division multiplexed LDR channels which must be combined and processed at the ground station.

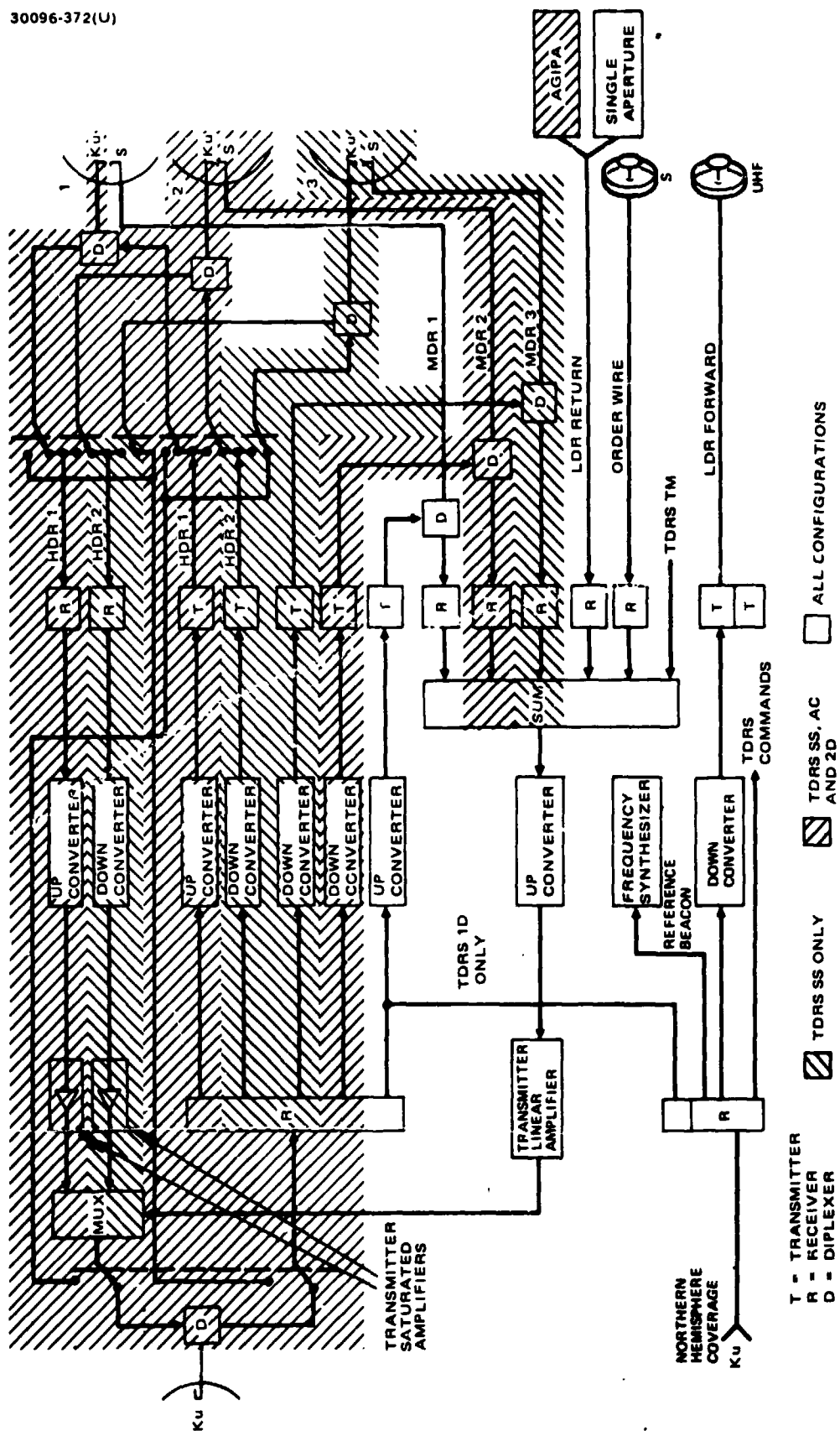


Figure 19. TDRS Repeaters

RF switching circuits are provided on the TDRS AC, TDRS SS, and TDRS 2D so that two of the S/Ku band antennas are available for maintaining the ground link if the primary ground link antenna should fail.

5.1.1 TDRS Receivers

Low noise transistor receivers are used extensively in all repeater designs. In addition, tunnel diode amplifiers and parametric amplifiers are included in several return links. An overview of the significant receiver characteristics is provided in Table 11.

The nomenclature employed in Table 11 is as follows. The first number in any box indicates the receiver noise temperature in kelvins, it is followed by a designation of the receiver type:

tran = transistor

TDA = tunnel diode amplifier

paramp = parametric amplifier

and the last number indicates the number of operational receivers in the repeater.

TABLE 11. TDRS REPEATER RECEIVER CHARACTERISTICS

		Frequency	TDRS 1D	TDRS AC	TDRS SS	TDRS 2D
Return from users	LDR	VHF	420/tran (1)	420/tran (10)	420/tran (10)	420/tran (6)
	MDR	S	420/tran (1)	100/paramp/tran (2)	100/paramp/tran (3)	100/paramp/tran (2)
	HDR	Ku	None	440/paramp/TDA (1)	440/paramp/TDA (2)	1170/TDA (1)
Forward from ground station	LDR	Ku	2000/tran*	1170/TDA	1170/TDA	1170/TDA
	**MDR and HDR	Ku	None	2600/tran	2600/tran	2600/tran

*LDR and MDR for TDRS 1D only

**TDRS SS, TDRS AC and TDRS 2D

One of the more stringent requirements for the part II configurations is the low noise temperature needed for MDR return link to satisfy the Space Shuttle service requirements. The parametric amplifiers in the HDR return links for TDRS AC and TDRS SS are included to minimize the user impact. In the TDRS 2D, mass contingency limitations precluded this feature.

5.1.2 TDRS Transmitters

The transmitters have received special attention in all the repeater designs, since their power levels and power conversion efficiencies are critical in determining the spacecraft power requirements. A summary of the transmitter characteristics is given in Table 12.

The entries in Table 12 show the dc power in watts and the EIRP in dBW. Two entries within one block indicate two available power levels selectable upon command. The numbers in parenthesis indicate the number of operational units.

Only one transmit level is available at UHF in TDRS 2D and TDRS AC, since simultaneous command and voice is not required as in TDRS 1D and TDRS SS. All MDR transmitter feature two power levels. Ku band TWT amplifiers with two power levels are also used in the TDRS AC and TDRS SS forward link to the HDR users. A solid state fixed power transmitter at Ku band is used in the TDRS 2D.

TABLE 12. TDRS REPEATER TRANSMITTER CHARACTERISTICS

Transmitter		Frequency	Part I	Part II		
			TDRS 1D	TDRS AC	TDRS SS	TDRS 2D
Forward to user	LDR	UHF	280/33 (1) 141/30	146/30 (1)	292/33 (1) 146/30	110/29 (1)
	MDR	S	91/47 (1) 23/41	100/47 (2) 25/41	100/47 (3) 25/41	100/47 (2) 25/41
	HDR	Ku	None	27/59 (2) 8.3/51	27/59 (2) 8.3/51	6.3/40 (1)
Return to ground station	LDR and MDR	Ku	32/51 (1)	8.4/53.1 (1)	8.4/53.1 (1)	8.4/44.8
	HDR	Ku	None	30/59 (1) 8.6/51	30/59 (2) 8.6/51	30/50.6 (1)

The return link transmitter designs for the repeaters differ largely because of differing ground link designs. For the TDRS SS and TDRS AC configurations a 3.82 meter antenna is used to increase the ground link capacity.

5.2 USER EQUIPMENT

User transponder equipment should be constructed using design approaches described for the TDRS repeaters. The principal difference in the detailed design is that the user equipment must operate in the complementary transmit and receive bands. Minimum mass designs are required to minimize the impact on user satellites. The power consumption of power amplifiers and transceiver equipment must also be minimized by using high efficiency components in their design and construction. Both LDR and MDR users require spread spectrum equipment.

A complete STDN ground station and TDRSS compatibility is assumed; thus, the user equipment shown is a complete TT&C package with the exception of digital decoding and encoding equipment. Complete redundancy is included. The mass and power characteristics are summarized in Table 13.

5.2.1 LDR User Equipment

The LDR user equipment, including pseudo noise correlators is planned with microwave integrated circuit construction to minimize equipment mass and production costs. The receivers utilize a transistor preamplifier to achieve a moderate noise figure, as RFI will generally limit the command link performance. Transmitters feature high efficiency transistor power amplifiers developing 5 watts of output power. Overall efficiency of a transmitter is estimated to be 50 percent. For equipment operation prior to acquisition of the TDRS carrier, a crystal oscillator provides the frequency reference for the transponder. An omnidirectional whip array antenna may be used on satellites using the LDR service.

5.2.2 MDR User Equipment

The S band MDR user equipment, as for the LDR users, is also implemented with microwave integrated circuit construction. Command receivers utilize a transistor preamplifier to achieve a moderate noise figure. A 5 watt transmitter is provided. The required link performance of 1 Mbps may be achieved with this transmitter power and with a directional antenna with approximately 20 dB gain. The directional antenna is controlled by commands received through an omnidirectional antenna. A mechanical positioner with stepper motor drive is used to position the antenna. Applications requiring lower data rates may be implemented with an array of antennas which are switched to achieve beam steering. Beams are broad and can be controlled by computer generated ground commands.

TABLE 13. USER TELECOMMUNICATIONS EQUIPMENT

Item	Number	Mass, kg	Power, watts
<u>LDR User VHF/UHF</u>		<u>5.8</u>	<u>15.0</u>
Receiver	2	1.0	1.0
Telemetry transmitter*	2	2.0	10.0
VCO control and frequency generator	2	0.3	1.0
Acquisition and data correlator	2	1.0	3.0
Antennas	1 set	1.5	-
<u>MDR User (1 Mbps) S Band</u>		<u>14.9</u>	<u>32.0</u>
Command receiver	2	0.8	1.0
Telemetry transmitter*	2	2.7	20.0
Frequency synthesizer	2	0.3	1.0
Signal processor	2	1.0	3.0
Diplexer	1	1.7	-
Antenna, omnidirectional	1	1.0	-
Antenna, directional	1	1.4	-
Gimbal	1	4.2	-
Gimbal driver	2	1.8	6.0
<u>HDR User (100 Mbps) Ku Band</u>		<u>27.2</u>	<u>62.3</u>
Command receiver, S band	2	0.8	1.0
Telemetry transmitter, S band	2	2.7	(20.0)
Tracking receiver, Ku band	2	5.1	5.8
Telemetry transmitter**, Ku band	2	5.2	45.5
Frequency synthesizer	2	0.5	1.0
Signal processor	2	1.0	3.0
Diplexer, S band	1	1.7	-
Diplexer, Ku band	1	0.2	-
Antennas, S band	1	1.0	-
Antennas, Ku band	1	3.0	-
Gimbal	1	4.2	-
Gimbal driver	2	1.8	6.0

* 5 watts RF power

** 12 watts RF power

The Space Shuttle communications requirements can be met for the return link with a transmitter power level of 40 watts and a 3 dB gain omnidirectional antenna; and with a low noise parametric preamplifier in the forward link. The mass and power requirements of such a transceiver have not been estimated.

5.2.3 HDR User Equipment

The HDR user equipment consists of a Ku band transmitter, a Ku band tracking receiver, a Ku band directional antenna and S band transceiver equipment for initial acquisition and for any direct contact with ground stations. The Ku band transmitter utilizes a TWT amplifier and a receiver implemented with waveguide circuitry. For a data link operating at 100 Mbps, a 12 watt RF power transmitter operating with a TDRS 3.82 meter antenna suffices. The antenna half-power beamwidth will be less than 0.5 degree for most HDR users, which necessitates special equipment for rapidly establishing the HDR user/TDRS link; an autotrack system is also provided to maintain correct pointing after link acquisition (see section 3.4.3). The antenna is positioned with a mechanical motor employing a stepper motor driver.

5.3 GROUND STATION

The TDRSS ground facilities consist of four major elements: 1) ground station, 2) GSFC switching, processing, and network control, 3) TDRS control center, and 4) user control centers. The relationship between these elements is shown in Figure 20.

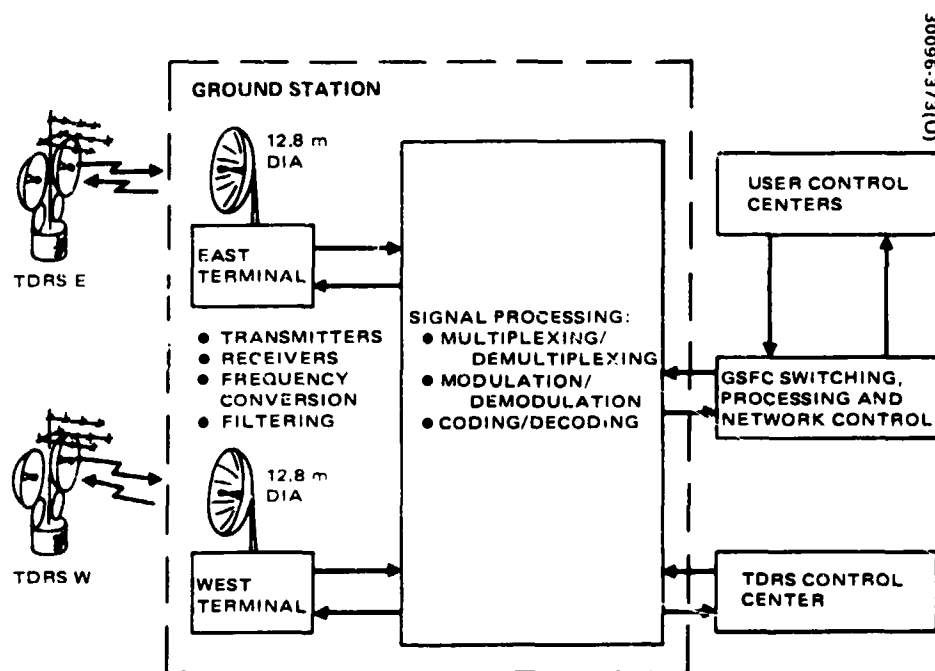


Figure 20. TDRSS Ground Facilities

The ground station is the interface between the TDRS control center, GSFC, and the TDR satellites. All modulation/demodulation, multiplexing/demultiplexing, and RF transmitting/receiving is performed at this facility. Also shown in the figure are three major portions of the basic ground station: 1) a terminal for maintaining RF communication with TDRS east, 2) a terminal for maintaining RF communication with TDRS west, and 3) a common area containing demodulation and processing equipment, which will be applied to signals from both terminals. For all configurations the link from ground station to the TDRS is implemented with a 12.8 meter diameter Ku band antenna. The RF terminals are of conventional design, but the signal demodulation and processing equipment, although not new in concept, has not been previously applied in the complexity required for simultaneous multiple user communication via the TDRSS. It should be mentioned that a third terminal may be required for communication with the in-orbit spare TDRS and for redundancy. This will require only a slight increase in the processing equipment and its configuration controls.

The major required equipment for a terminal are listed below.

- 1) Ku band/S band antenna - 12.8 meter diameter parabolic reflector
 - a) Ku cassegrain feed circular polarization
 - b) S band near focus feed - circular polarization
- 2) Receivers
 - a) Ku band at rear of reflector - 3.9 dB noise figure
 - b) S band in terminal structure - 4 dB noise figure
- 3) Power amplifiers - Two plus standbys

The required outputs are as follows:

- a) MDR and HDR signals amplified in one: accounting for estimated line loss (3 dB) and required backoff (3 dB)
MDR: 100 watts per channel
HDR: 400 watts per channel
- b) LDR reference, beacon, and TDRS commands in the other:
LDR: 1000 watts
Beacon: 20 watts
TDRS command: 20 watts

5.3.1 Signal Processing

The required demodulation and signal processing equipment for return links includes:

- 1) LDR signal processor for each user including range and range rate signal extraction
- 2) MDR PSK demodulator for each channel
- 3) HDR PSK demodulator and decoder
- 4) Order wire demodulator and processor

The required modulation and processing equipment for the forward links includes:

- 1) LDR: PN/PSK modulator
- 2) MDR: PN/PSK modulator for each channel
- 3) HDR: PSK modulator

6. TDRS CONFIGURATIONS

Figure 21 depicts the four final TDRS configurations developed:

- Delta 2914 launched TDRS configuration 1
- Atlas Centaur launched TDRS configuration
- Space Shuttle launched TDRS configuration
- Delta 2914 launched TDRS configuration 2

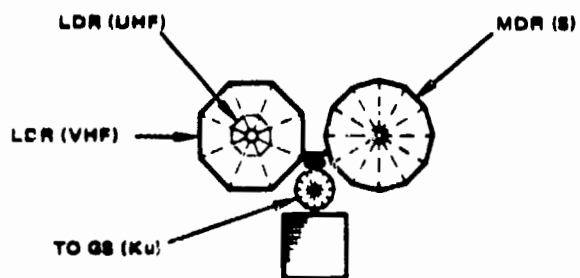
The TDRS 1D was developed during Part I of the study, whereas the remaining configurations were developed during Part II of the study. Subsystem concepts and technology from current Hughes commercial and military space programs were used for all configurations to the maximum extent possible.

The TDRS 1D configuration is a relatively conventional design with the spacecraft mass minimized by use of lightweight materials, such as beryllium, and improvements in subsystem designs.

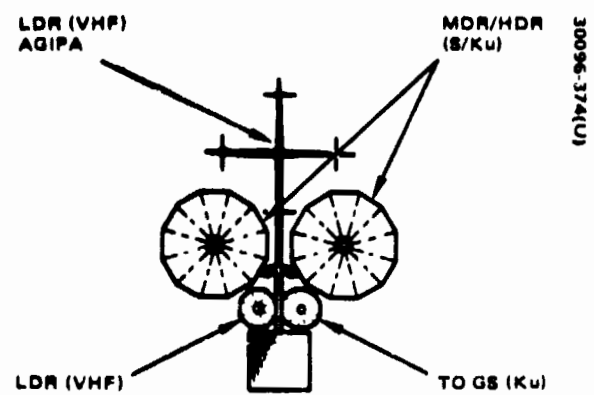
The TDRS AC configuration is an adaptation of the Intelsat IV bus, with new antennas and electronics, to the TDRS mission requirements. Since the Atlas Centaur performance has increased from the start of the Intelsat IV program, the additional antenna and electronic mass can be readily accommodated.

The TDRS SS configuration is similar to the TDRS AC configurations after deployment; however, the relatively large payload bay of the Space Shuttle as compared to the Atlas Centaur payload fairing permits a simpler antenna stowage. Furthermore, a new dual spin concept has been employed resulting in both end platforms being despun. The latter feature permits a more convenient antenna deployment. The performance potential of the Space Shuttle allows a rather generous growth margin for this configuration.

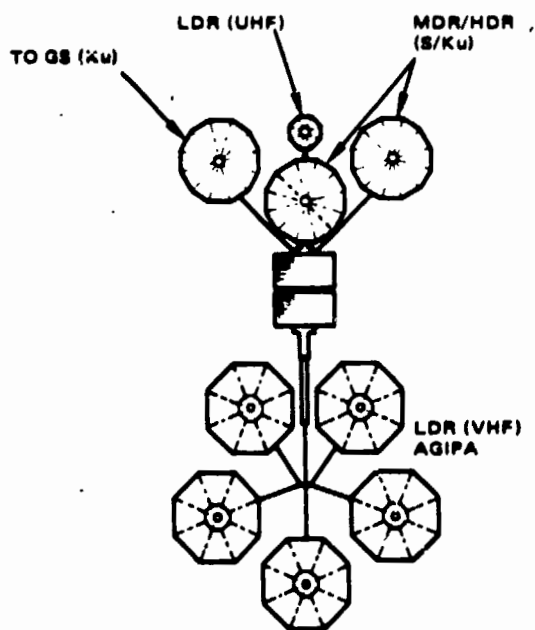
The TDRS 2D configuration employs lightweight materials and also lightweight subsystem technology: AGIPA with YAGI elements, LSI and MOS-MSC for electronic equipment, and bipropellant RCS. Furthermore, some duty cycle operations are imposed on the user service to save mass in the electric power subsystem.



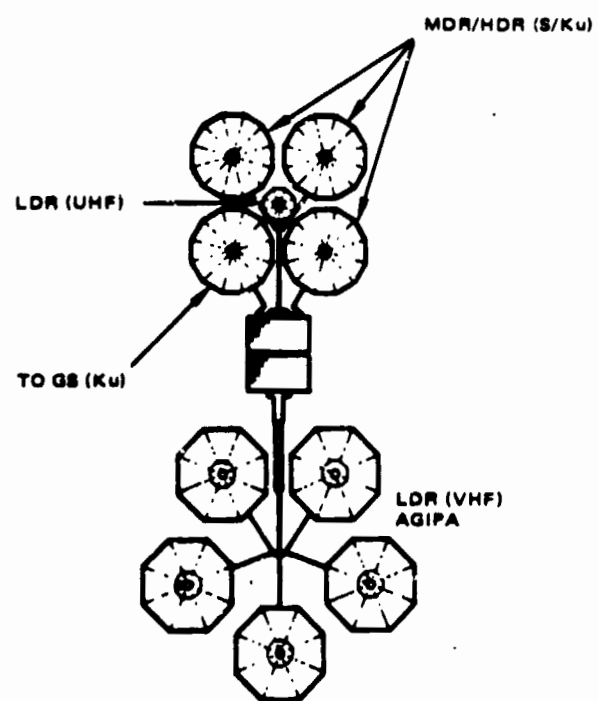
DELTA 2914 LAUNCHED
CONFIGURATION (1)



DELTA 2914 LAUNCHED
CONFIGURATION (2)



ATLAS-CENTAUR
LAUNCHED CONFIGURATION



SPACE SHUTTLE
LAUNCH CONFIGURATION

Figure 21. Four Final TDRS Configurations

Spacecraft mass summaries for all configurations are provided in Table 14. Electric power requirements and the power available from the solar panels and batteries for all configurations is summarized in Table 15.

A discussion of the general design approach which is similar for all configurations is included in subsection 6.1. Subsection 6.1 discusses the general design approach of all configurations, subsections 6.2, 6.3, 6.4, and 6.5 summarize the external features of the configurations, primarily antennas, and subsection 6.6 reviews the subsystem design features and technology.

TABLE 14. TDRS CONFIGURATION MASS SUMMARIES

Subsystem/Item	Mass, kg			
	TDRS 1D	TDRS AC	TDRS SS	TDRS 2D
Repeater	55.1	73.0	99.9	68.2
Telemetry and command	18.1	19.5	19.5	12.9
Antennas	36.6	96.5	113.5	53.0
Attitude control	23.5	32.8	56.1	20.0
Reaction control (less propellant)	11.4	18.0	18.5	10.5
Electrical power	61.5	93.3	151.0	41.1
Wire harness	11.5	30.0	30.0	15.0
Apogee motor (burned out)	25.5	57.0	77.0	25.4
Structure	68.2	236.3	270.0	70.5
Thermal control	10.0	30.0	30.0	8.8
Contingency	25.6	134.3	175.3	26.1
Final mass in orbit	347.0	821.3	1040.8	357.5
RCS propellant*	38.0	141.0**	79.2	25.0
Apogee motor expendables	293.0	652.7	980.0	295.5
Separation mass	678.0	1615.0	2100.0	678.0

*Propellant, including transfer orbit requirements, provided for full launch vehicle capability.

**Includes 77.4 kg RCS propellant used to augment apogee injection.

TABLE 15. TDRS ELECTRIC POWER SUMMARY, WATTS (POWER AT BUS VOLTAGE)

Link Power Requirements Including Transmit And Receive Operations						
			TDRS 1D ⁽¹⁾	TDRS AC	TDRS SS ⁽¹⁾	TDRS 2D ⁽¹⁾
LDR link	Command mode		155	156	168	127
	Voice mode		152		151	
MDR link	47 dBW EIRP		96	106	116	115
	41 dBW EIRP		24	31	35	33
HDR link	EIRP to user 59 dBW	EIRP to L 59 dBW		67	73	
		EIRP to GS 51 dBW		49	53	
	EIRP to user 51 dBW	EIRP to GS 59 dBW		46	51	
		EIRP to GS 51 dBW		28	30	
	EIRP to user 40 dBW	EIRP to GS 50.6 dBW				49
Ranging transponder	Transmit mode		26	24	26	26
	Receive mode		2	2	2	2
Power Available For Telecommunications Service And Ranging						
Solstice season from solar panel			246	444	635	262
Eclipse ⁽²⁾ season	From solar ⁽³⁾ panel	10 hours ⁽⁴⁾	221	367	589	258
		12.8 hours ⁽⁵⁾	281	476	683	295
	Average battery power for 1.2 hours ⁽⁶⁾		241	346	783	98
Spacecraft Power Summary						
TDRS repeater residual loads			45	27	29	30
Spacecraft subsystems			73	69	88	72
Battery charging			60	109	94	37
Solar ⁽³⁾ panel output	Solstice season		364	540	752	364
	Eclipse season		399	572	800	397
Average battery power for 1.2 hours			359	442	900	200

(1) 8 percent less power required if links operated from batteries

(2) Maximum eclipse condition of 1.2 hours

(3) At the end of 5 years in orbit

(4) Battery charging mode, 10 hours daily

(5) No battery charging, 12.8 hours daily

(6) Average power may be exceeded up to the total energy capacity of the batteries

6.1 GENERAL DESIGN APPROACH

The Hughes Gyrostat stabilization concept has been employed to provide a fully stabilized platform for the payload while exploiting the simplicity and long life advantages associated with spinning satellites. The two main elements of the spacecraft are the spinning rotor and the despun, earth oriented platform containing the communication repeater and its antennas.

Spin stabilization is accomplished by rotating the section of the spacecraft containing propulsion and power equipment. The angular momentum developed provides a resistance to external torques and minimizes the number of attitude corrections required throughout the mission. The Gyrostat principle of stabilization is used in this design of the TDRS. This approach allows large sections of the spacecraft to be despun, thereby accommodating the antennas and communication electronic equipment required for this mission on the stabilized despun platform.

The despun section houses the communication equipment and some of the telemetry, tracking, and command (TT&C) equipment. To achieve a benign thermal environment for the communication subsystem and other critical equipment, a thermal control cavity is created inside the spinning solar cell array in which all temperature-sensitive equipment is placed. Antennas are mounted off the platform on a mast type support structure.

The spinning section supports and houses the propulsion, electrical, power, attitude control, and some of the TT&C equipment. The apogee motor is installed in the central thrust tube. RCS propellant tanks are mounted on ribs extending from the thrust tube to the solar cell array. Batteries, battery controllers, despin control electronics, and TT&C equipment are mounted on the ribs and on small equipment platforms spanning the ribs.

The aft end of the spacecraft (apogee motor end) is sealed off by a rotating thermal barrier. This barrier has an external surface of stainless steel to protect the spacecraft from the intense heating caused by the apogee motor plume as well as the axial RCS jet plume. The forward end of the rotating drum cavity is sealed off by a spinning sunshield. This conical shell structure is covered with aluminized teflon to reject solar input while at the same time radiating the heat generated by the communication equipment. The spin of these primary thermal control surfaces provides a low gradient thermal environment for the communication electronics and primary spacecraft control elements.

A rotating interface, consisting of conventional ball bearings and slip rings, sustains the relative motion between the two sections, permits signal transfer to take place, and affords an electrical path over which power from the solar panels and batteries can flow to the repeater payload.

6.2 DELTA 2914 LAUNCHED TDRS CONFIGURATION 1

The TDRS 1D configuration depicted in Figure 22 uses conventional subsystem concepts and technology from current Hughes commercial and military space programs. Spacecraft mass was minimized by use of light-weight materials, such as beryllium, and improvements in subsystem design.

The TDRS 1D provides LDR and MDR service. Short backfire type antennas are provided for the LDR user VHF return link and the two channel UHF forward link. An S band parabolic reflector antenna is provided for both forward and return link service for the MDR user. These antennas are folded and stowed within the payload fairing during launch. The TDRS to ground link at Ku band incorporates a high gain parabolic reflector antenna. Both the S band and Ku band paraboloid antennas are installed on two-axis gimbals. S band short backfire antennas are provided for the trilateration transponder and order wire service. A VHF turnstyle array is provided for backup TT&C operation. The antenna characteristics are summarized in Table 16.

TABLE 16. TDRS 1D ANTENNA CHARACTERISTICS

		Frequency	Minimum Gain Over FOV, dB	Antenna Type	Diameter, m
LDR	Forward	UHF	12.5	Short backfire	1.43
	Return	VHF	11.2	Short backfire	3.82
MDR	Forward	S band	36.0	Parabolic reflector, focus feed	3.82
	Return		36.7		
Order wire		S band	13.1	Short backfire	0.267
Ground Link	Forward	Ku band	18.5	Horn	—
	Return		44.0	Parabolic reflector	1.43
Transponder	Forward	S band	13.5	Short backfire	0.267
	Return		13.0		

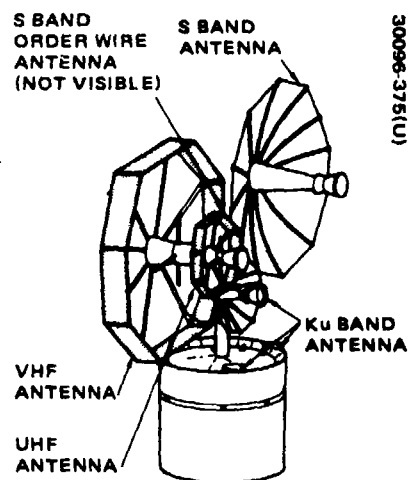


Figure 22. Delta 2914 Launched TDRS Configuration 1 - (TDRS 1D)

6.3 ATLAS CENTAUR LAUNCHED TDRS CONFIGURATION

The TDRS AC configuration shown in Figure 23 is an adaptation of the Intelsat IV bus (with new antennas and electronics) to the TDRSS mission requirements. Since the Atlas Centaur performance has increased from the start of the Intelsat IV program, the additional mass can be readily accommodated.

The TDRS AC repeater provides one forward channel for LDR service, two forward and return channels for MDR service, and one forward and return channel for HDR service. The MDR and HDR service is implemented with two S/Ku band antennas, thus time sharing between the MDR and HDR services is required. This configuration utilizes both forward and aft mounted antennas to minimize solar torque. The high gain MDR/HDR, and TDRs to ground station link antennas are mounted forward. This position minimizes cable and waveguide runs to electronic equipment mounted in the spacecraft, and also provides for a more rigid and thermally stable mount

TABLE 17. TDRS AC ANTENNA CHARACTERISTICS

		Frequency	Minimum Gain Over FOV, dB	Antenna Type	Diameter, m
LDR	Forward	UHF	12.5	Short backfire	1.43
	Return	VHF	18.8	Five element AGIPA	Element 4.35
MDR	Forward	S band	35.5	Parabolic reflector, focus feed	3.82
	Return		36.2		
HDR	Forward	Ku band	52.8	Parabolic reflector, Cassegrain feed	3.82
	Return		51.9		
Order wire		S band	13.1	Short backfire	0.267
Ground Link	Forward	Ku band	18.5	Horn	—
	Forward		51.9	Parabolic reflector	3.82
	Return		52.8		
Transponder	Forward	S band	13.5	Short backfire and bicone	0.267
	Return		13.0		

for these narrowbeam antennas. A forward location of the UHF broadband antenna is also selected to minimize power loss in the transmission lines running from the transmitter to the antenna. The LDR return link service is implemented with a five-element, ten channel AGIPA configuration which is deployed aft. The VHF elements are less sensitive to alignment errors and cable runs over the required distance do not result in excessive losses. The array is deployed from the forward (despun) platform by a combination of an Astromast and pivoted linkages. The Astromast is a low mass deployable truss structure which can achieve the long deployment required with a high stiffness and highly compact stowage with virtually no shadowing of the solar cell arrays. The antenna characteristics are summarized in Table 17.

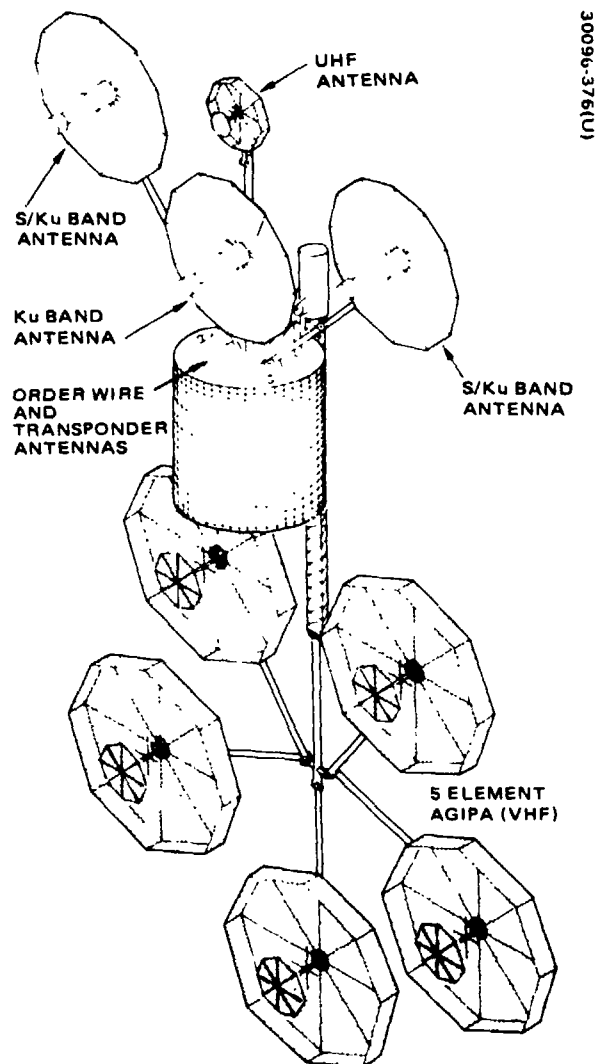


Figure 23. Atlas Centaur Launched TDRS Configuration - (TDRS AC)

6.4 SPACE SHUTTLE LAUNCHED TDRS CONFIGURATION

The TDRS SS configuration depicted in Figure 24 is similar to the TDRS AC configuration after deployment; however, the relatively large payload bay of the Space Shuttle as compared to the Atlas Centaur payload fairing permits a convenient and simple antenna stowage. The Transtage was selected to provide a cost effective booster to inject an assemblage of three spacecraft simultaneously into synchronous transfer orbit. The injection capability is approximately 6600 kg. Each spacecraft has been allocated 2100 kg, allowing 300 kg for mission peculiar equipment and installation onto the Transtage.

The TDRS SS features a dual platform arrangement with equipment platforms located at both ends of the cylindrical body. Thus a configuration with low solar pressure torque and with reasonable short cable and waveguide runs between platform mounted communication equipment and their antennas is attained.

TABLE 18. TDRS SS ANTENNA CHARACTERISTICS

		Frequency	Minimum Gain Over FOV, dB	Antenna Type	Diameter, m
LDR	Forward	UHF	12.5	Short backfire	1.43
	Return	VHF	18.8	Five element AGIPA	Element 4.35
MDR	Forward	S band	35.5	Parabolic reflector, focus feed	3.82
	Return		36.2		
HDR	Forward	Ku band	52.8	Parabolic reflector, Cassegrain feed	3.82
	Return		51.9		
Order wire		S band	13.1	Short backfire	0.167
Ground Link	Forward	Ku band	18.5	Horn	—
	Forward		51.9	Parabolic reflector	3.82
	Return		52.8		
Transponder	Forward	S band	13.5	Short backfire and bicone	0.267
	Return		13.0		

The TDRS SS repeater provides two forward channels for LDR service, three forward and return channels for MDR service and two forward and return channels for HDR service. The MDR and HDR service is implemented with three S/Ku band antennas; thus, time sharing between the MDR and HDR services is required. LDR return link service is provided by the five element ten channel AGIPA as described for the TDRS AC configuration. The antenna characteristics are summarized in Table 18.

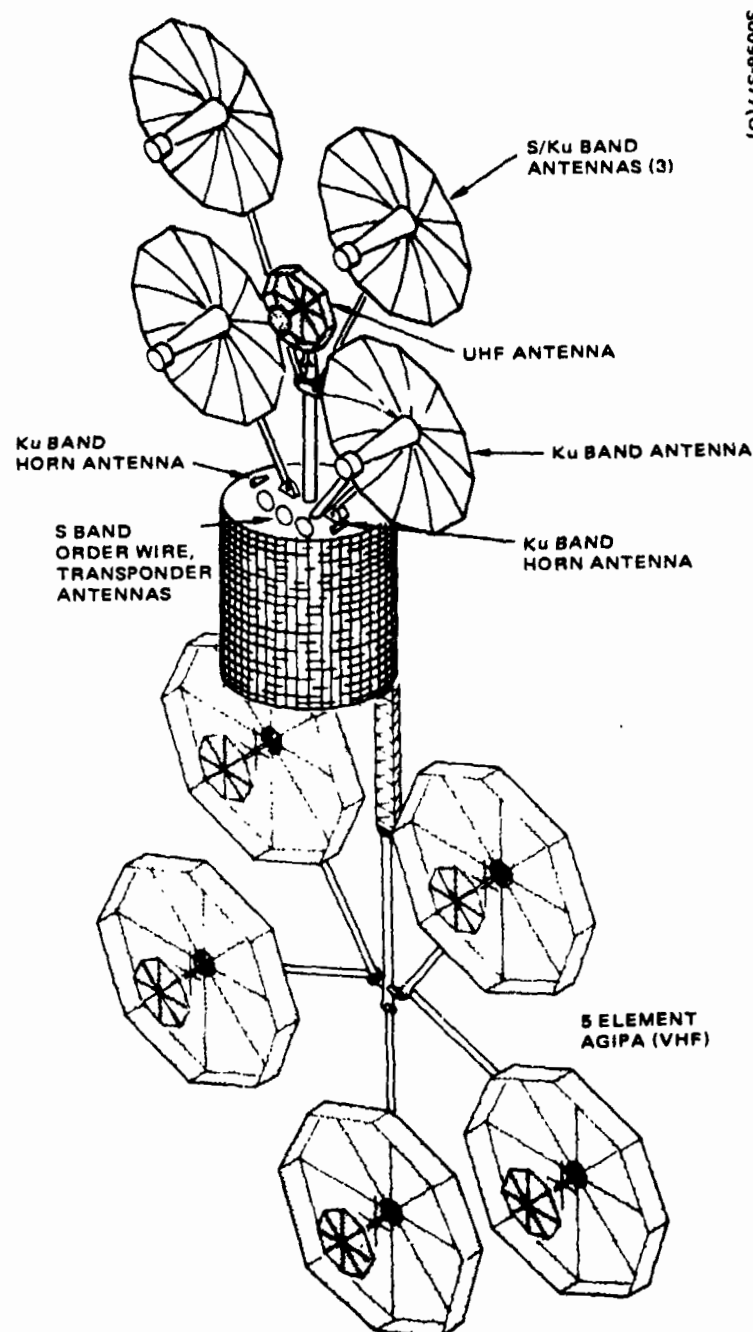


Figure 24. Space Shuttle Launched TDRS Configuration - (TDRS SS)

6.5 DELTA 2914 LAUNCHED TDRS CONFIGURATION 2

The TDRS 2D configuration shown in Figure 25 uses not only lightweight materials but also emphasizes lightweight subsystem technology: AGIPA with Yagi elements, microwave integrated circuits for repeater electronics, MOS/LSI circuitry for TT&C digital equipment, and bipropellant RCS. Furthermore, some duty cycle operation is imposed on the user service to save mass in the electric power subsystem.

The TDRS 2D repeater provides one forward channel for LDR service, two forward and return channels for MDR service, and one forward and return channel for HDR service. The MDR and HDR service is implemented with two S/Ku band antennas; thus, time sharing between MDR and HDR services is required. The LDR return link utilizes an AGIPA consisting of four VHF-Yagi elements. These are deployed on booms off the main support mast forward of the spacecraft body. Paraboloid reflector antennas are provided for MDR and HDR links. They incorporate dual S/Ku band feeds so that the type of service is established by switching of appropriate repeater equipment. Stowage during launch is achieved by collapsing the

TABLE 19. TDRS 2D ANTENNA CHARACTERISTICS

		Frequency	Minimum Gain Over FOV, dB	Antenna Type	Diameter, m
LDR	Forward	UHF	12.5	Short backfire	1.43
	Return	VHF	14.7	Four YAGI element AGIPA	—
MDR	Forward	S band	35.5	Parabolic reflector, focus feed	3.82
	Return		36.2		
HDR	Forward	Ku band	52.8	Parabolic reflector, Cassegrain feed	3.82
	Return		51.9		
Order wire		S band	13.1	Short backfire	0.267
Ground Link	Forward	Ku band	18.5	Horn	—
	Forward		44.0	Parabolic reflector	1.42
	Return		45.1		
Transponder	Forward	S band	13.5	Short backfire and bicone	0.267
	Return		13.0		

paraboloid reflector and folding the supporting linkage. A fixed aperture Ku band antenna is provided for the TDRS to ground station link. All high gain antennas are provided with two axis gimbals. Trilateration transponder and order wire service for manned users is implemented through broadbeam S band short backfire antennas. The antenna characteristics are summarized in Table 19.

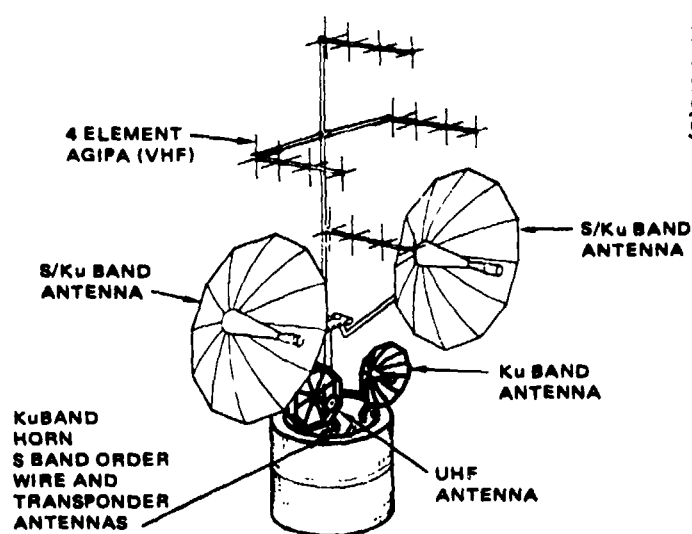


Figure 25. Delta 2914 Launched TDRS Configuration 2 - (TDRS 2D)

6.6 TDRS SUBSYSTEM DESIGN FEATURES AND TECHNOLOGY

A brief discussion of the key design features of the subsystems and their technology are included in subsections 6.6.1 through 6.6.9.

Long lifetime mission success requires the use of high reliability parts and the use of redundancy for active components. Exceptions occur for items such as the apogee motor, structure, despin bearing assembly, and antennas where it would be prohibitive from mass considerations alone to provide redundancy. In these items, safety factors are employed in their design and assured by test programs. All electronic units are redundant in the TDRS configuration presented; thus, no single failure will cause a loss of mission objectives.

6.6.1 Repeaters

The VHF receivers associated with the LDR AGIPA return provide redundant downlink channels. This receiver incorporates lightweight surface wave bandpass filters preceded by preamplifiers which establish a low noise figure. Hybrid microcircuit packaging is also used to achieve low mass for the unit.

The S band transmitter and receiver from MDR users are capable of transmitting and receiving at any frequency within the designated bands. A parametric preamplifier is used to maintain a low receiver noise temperature. The power amplifiers for the S band transmitter are solid state, providing an output power of 23.5 watts. This is reduced by the line losses to 12.5 watts at the antenna, yielding the required 47 dBW EIRP. The order wire S band receiver noise figure and antenna gain of this receiver allow approximately 1 kHz of data to be transmitted by the user to the ground station via the TDRS.

The Ku band HDR forward link transmitter is implemented with a 100 mW solid state amplifier which saves some mass relative to the use of TWT amplifiers, and the return link receiver utilizes a TDA preamplifier to achieve a moderate noise figure for the TDRS 2D configuration.

The TDRS AC and TDRS SS utilize TWT amplifiers for the HDR forward link and parametric preamplifiers in the receivers to maximize communication capacity, as these configurations are not as constrained by launch vehicle payload limitations. The TDRS return link to the ground station utilizes TWT amplifiers. Service is provided with a single amplifier operated in a saturated mode. LDR, MDR, and TDRS telemetry share a second downlink channel powered by a TWT amplifier operated in the linear region to avoid intermodulation distortion of the user data. The forward link receivers utilize TDA preamplifiers to achieve moderate noise figures.

An S band transponder for TDRS trilateration backup T1&C operation is provided. Equipment construction is similar to that of the MDR repeater equipment.

The TDRS 2D configuration places severe demands upon hardware design implementations by requiring minimum size, mass, and power while providing nearly the same telecommunications services as larger spacecraft payload configurations. These demands have placed design emphasis on utilization of hybrid circuits and microwave integrated circuits (MIC) technology with thick and thin film circuits. Hybrid microcircuit techniques are also applied to IF circuit designs and voltage regulators and power supplies.

There have not been many microminiature hybrid devices used to date in communications satellites or spacecraft in general. However, of those which have been used in recent communications satellite designs, there are no known failures in over 500,000 operating hours. High reliability is also substantiated by field test and life test results of Hughes missile and avionics subsystems using hybrid circuit designs. Compared to discrete circuit devices, the hybrid circuit failure rates are better by a factor of 3 to 1.

Impatt amplifier techniques are used for the HDR Ku band, solid state forward transmitter power amplifier in the TDRS 2D configuration. The requirement of 100 mW output at 14.7 GHz is achievable with present day silicon diodes. The 30 dB gain can be easily achieved with either a three stage amplifier or a two stage injection locked oscillator. The major technical design problem is to achieve high efficiency. An efficiency of 2 percent is expected to be obtained using small diodes made with currently available technology.

The TDRS TWT amplifiers are a scaled version of existing or presently under development spacecraft TWTs. The key performance parameter is efficiency. The 32 percent efficiency is achievable by operating the TWT at a voltage about 8 percent over that which corresponds to maximum gain.

Each TWT satellite application usually has such specific requirements that some new development is necessary; the TDRS TWT development should emphasize efficiency and low mass.

6.6.2 Telemetry, Tracking, and Command

The TT&C subsystem is derived from that used on the Intelsat IV. It features PCM and FM real time modes of operation for spacecraft telemetry. The PCM mode is used for all attitude, thermal, power, and status information, including command verification. Spinning and despun redundant encoders are interconnected by means of the electrical contact rings installed in the despun bearing assembly. Telemetry from the spinning encoder is interleaved with telemetry from the despun side on a word-by-word basis. The composite bit stream is converted to a Manchester code format which is

then used to phase modulate either the S band telemetry transmitter of the telemetry carrier of the TDRS/ground station Ku band link.

The FM real time mode is used for transmitting attitude data (sun sensor pulses, earth sensor pulses, platform index pulses, and command execute pulses). The occurrence of a pulse coherently switches the frequency of an IRIG channel 13 subcarrier oscillator from its pilot tone to a different frequency, depending on the kind of pulse present. The output is connected via a slip ring to the despun encoder, the output of which phase modulates the telemetry transmitter of the primary telecommunication service system at the Ku band frequency or the backup telemetry transmitter and command receiver at S band.

Spacecraft command is performed through two cross-strapped command systems. Redundant decoders are located on both the spun and despun portions of the spacecraft. A total of 127 commands are available for controlling the state of the rotor, while 255 commands are available for the despun platform.

The command system is capable of executing jet firing commands in phase with the spin of the satellite. This is performed at the ground station by synchronizing the execute tones with sun or earth pulses received via real time telemetry. The repetitive command mode is also used for antenna pointing. Tracking commands are transmitted as required to maintain the antenna pointing at MDR user satellite. Antenna acquisition commands are also received prior to autotracking of HDR user satellites.

Extensive use of MOS-LSI circuitry is planned in order to achieve a minimum mass for the TT&C subsystem in the TDRS 2D configuration. Principal circuits using this technology are those performing digital and timing functions. Advantages of the technique include lower subsystem mass and improved reliability. This technology has been demonstrated on other space programs performed by Hughes.

6.6.3 Antenna and Positioning Mechanisms

The antenna technology required for this program includes extensive use of deployable, minimum mass construction. The deployable reflector antenna configurations are based on engineering model development proceeding at Radiation, Incorporated in Melbourne, Florida.

LDR return links are implemented with a single short backfire element for the TDRS 1D configuration. The TDRS AC and TDRS SS configurations use an array of five short backfire antennas in an AGIPA configuration. An AGIPA array of four Yagi elements is utilized for the TDRS 2D configuration. The latter design presents a low area to incident sunlight, thereby minimizing the solar radiation pressure torques. The elements also lend themselves to low mass construction and ease of deployment. A short backfire element is selected for the LDR forward link operating at UHF. This

element develops the required performance with high efficiency and with minimum mass using rib and mesh construction.

The high gain S/Ku band and Ku band antennas are a deployable rib-mesh design of 3.82 meters (12.5 feet) diameter and an f/D of 0.4. The antennas are configured with 12 ribs. A double mesh technique is utilized to achieve a surface contour of 0.25 mm rms accuracy. The subreflector is constructed as a shaped honeycomb sandwich with fiberglass face sheets and aluminum foil for RF reflectivity. The reflective mesh is open gold plated chromel R knit, and its contour between ribs is adjusted by tension ties to a back mesh. A redundant torque spring and motor drive system unfurls the antenna reflector.

Ku band horns are provided for TT&C operation to assure that this function is not interrupted if the linkup using the high gain antenna is broken. S band short backfire antennas are used for order wire and transponder operation.

Two axis drives are used for the high gain S/Ku band antenna and the Ku band reflector antenna for azimuth and elevation control. The drivers use stepper motors and a harmonic gear reduction drive. The motors incorporate magnetic detent, thereby avoiding power consumption while in standby operation. This magnetic detent is effective for each single step of the motor; therefore, no accuracy anomalies occur when power is removed.

The gimbal assembly is supported in each axis by the preloaded angular contact ball bearings of the motor drive assembly and by an outboard radial deep groove bearing. The bearing size is determined by launch loads imparted to the mechanism and bearing spacing is chosen sufficient to minimize error due to bearing runout. Dry film lubrication is used throughout the mechanisms for temperature range compatibility and to avoid the need for sealing the moving elements. The lubrication technique has been proven on previous Hughes programs and is amenable to the accuracy requirements and the torque capability of the drivers. The S band antenna positioner employs coaxial rotary joints for low RF loss. The Ku band drive mechanism has rotary waveguide RF power transmission across its axes.

6.6.4 Attitude Control and Despin Bearing Assembly

The attitude control system establishes the spacecraft attitude, provides a stable platform for antenna positioning, and monitors the orientation of the vehicle spin vector and despun platform azimuth for precision antenna pointing. Spin stabilization is used to absorb cyclic torque disturbances and to minimize the number and frequency of reaction jet firings required for orientation control. Attitude control of the despun section is autonomous and uses earth sensor data to orient the despun section toward the center of earth. A magnet/pipper coil pair located in the bearing and power transfer

assembly (BAPTA) establishes the relative phase relationship between the rotor and the platform. Nutational stability is provided through the passive nutation damper mounted on the despun platform, along with active control through the despin control system and the active nutation control system.

The despin BAPTA is the structural interface between the spun and despun sections. The bearing lubrication system consists of four sintered nylon reservoirs, two porous ball retainers, the bearing metal parts, and the internal walls of the motor/bearing subassembly. The oil used to lubricate the bearings is a mixture of Apiezon C and lead naphanate. The lubricant is vacuum impregnated into the bearing parts prior to assembly. Redundant, brushless, resolver commutated dc torque motors are provided. The motors are segment wound on a common lamination stack and two fully redundant resolvers are provided. Power and signal transfer from spun to despun sections of the satellite is accomplished with a dry lubricated slip ring assembly.

All of these design concepts have been used on previous Hughes space programs.

6.6.5 Reaction Control

Orbital propulsion is obtained by catalytic decomposition of anhydrous hydrazine for all TDRS configurations except TDRS 2D. Hydrazine propulsion systems have been proven on the ATS program and utilized successfully on Intelsat IV, Telesat, and others. The reaction control subsystem (RCS) performs the functions of attitude and on-orbit velocity control. Spinup is also performed for the TDRS AC and TDRS SS configurations. The Delta third stage performs spinup for TDRS 1D and TDRS 2D configurations. The system is divided into half systems with each half system capable of performing maneuvers. Mission propellant is divided between the half systems. Stationkeeping and attitude control propellant for 7 years have been included in the design.

A bipropellant RCS design is featured for the TDRS 2D configuration. This has been selected rather than the hydrazine monopropellant system designs used on current spin stabilized satellites in order to conserve propellant mass. The thruster selected is the TIROC 1N which produces 1 newton of thrust using monomethylhydrazine and nitrogen tetroxide propellants. The specific impulse is approximately 50 percent greater than that attainable with the catalytic decomposition hydrazine thrusters, thus reducing propellant consumption by one third.

The bipropellant thruster and associated propellant control valves have been developed during an intensive 6 year program by Arbeitsgemeinschaft Für Raketentechnik Und Raumfahrt an der Universität Stuttgart E. V., Stuttgart, West Germany. The propellant control valve employs an electromagnet to draw a flexure mounted poppet away from the valve seat. The valve is held closed by the spring flexure force. When power is applied, the

electromagnetic forces overcome the flexure spring forces and the valve opens. When power is removed, the valve closes.

The bipropellant thruster, including propellant valves is capable of delivering more than 1 million seconds of steady state operation with the external case temperature never rising above 400 K. On the other hand, the thruster, including valves, has demonstrated the capability to deliver over 10 million duty cycles. The demonstrated specific impulse ranges from 260 seconds for very short duration pulses to 290 seconds for steady state operation. The propellant valves developed in conjunction with this thruster have demonstrated over 1 billion cycles without failure. Tests performed with the thruster have shown that the impulse bit produced is a linear function of valve on time from 3 milliseconds to greater than 150 milliseconds, repeatable to ± 6 percent. In addition, the thruster has demonstrated the ability to operate in an unregulated blowdown mode with tank pressure varying from 2.76 MN/m² down to 0.69 MN/m² and mixture ratios of 1.5 to 2.5.

Other components to be used were initially developed for the monopropellant hydrazine systems. All materials used in these components which are wetted by the propellants are compatible with both the monomethyl hydrazine and the nitrogen tetroxide. Therefore, flight proven tanks, fill and drain valve, pressure transducer, latch valves, and filters can be incorporated into the bipropellant system.

6.6.6 Electrical Power

Electrical power is provided by a spinning solar cell array. A portion of the solar array power is used to charge nickel-cadmium (NiCd) batteries to provide power during periods of solar eclipse and to supplement the power available from the solar cell array during period of peak demand. The solar array features the use of currently available 22 x 62 mm solar cells, 0.25 mm thick. The cells are covered with 0.15 mm ceria doped microsheet.

The electric power subsystem for TDRS 1D, 2D, and SS configurations include two Ni-Cd batteries with active battery discharge control. The batteries are composed of 16 series cells. Cell size is selected for each configuration to match the loads required during solar eclipse operation. Battery discharge regulators boost the battery output to a nominal 25.5 volt line. The battery discharge regulator circuit is of the boost choke type and uses pulsewidth modulation. It has a minimum number of power transistors and requires minimum input line filtering. To reduce power transistor stress and to minimize output filter size, each circuit is two phase, with forced current sharing between phases.

The TDRS AC electric power subsystem utilizes previously designed Intelsat IV hardware to minimize development cost. This configuration uses 26 cells in series discharging directly into the power bus during solar eclipse. Charging is accomplished by boost charge strings of solar cells. As the boost charge strings are usable only for battery charging, this

configuration is not suitable where minimum size solar cell arrays or minimum mass subsystem designs are required.

6.6.7 Apogee Injection Motor

The only motor currently under development to serve as a synchronous apogee motor for a Delta 2914 launch vehicle payload is Thiokol's TE-616, being built for the Canadian Technology Satellite. The only other motor design offering a significant mass advantage is a Hercules motor, which was selected as the baseline. For the TDRS mission, approximately 10 kg of the spacecraft mass could be saved. The mass savings are due entirely to the higher performance of a composite-modified, double-base (CMDB) propellant produced by Hercules, Inc. The selected propellant has been used in over 850 Hercules production motors. Its performance has been well characterized in over 65 static and 190 flight tests and has remained consistent in motors fired after a period of 7 years.

The SVM-4A motor built by Aerojet for the Intelsat IV is used as the synchronous apogee motor for the TDRS AC. It has been successful on all four Intelsat IV launches to date. The SVM-4A is undersized for the improved Atlas Centaur launch vehicle separated mass capability of 1720 kg. However, the final on-orbit mass has been maximized by using the maximum amount of additional hydrazine that can be stored in the existing Intelsat IV reaction control subsystem (77.4 kg) and performing a 6 degree perigee plane change during transfer orbit injection.

The second candidate apogee motor for an Atlas Centaur launch is a modified version of the TE-M-364-4 to be built by Thiokol for the FLTSATCOM program. The exact propellant mass has not been established, but the satellite will be launched from the improved Atlas Centaur. The motor will match the full payload capability of the improved Atlas Centaur launch vehicle at an optimum design point.

An off loaded version of the TE-M-364-4 may be used to match satellites launched by the Space Shuttle/Transtage launch vehicle combination. This is selected from a cost and reliability standpoint, as the satellite mass is not at a critical design value.

6.6.8 Structure

The structural design for Delta launched configurations is based predominantly on the use of beryllium to conserve spacecraft mass. Its principal advantage is obtained in primary structure where stiffness is a critical design condition. This applies to the thrust cone, equipment mounting platforms and the antenna support mast. This material has been used in spacecraft structures for at least 5 years.

The structure for TDRS AC and TDRS SS configurations is based primarily on the use of aluminum and magnesium for primary structure. The TDRS AC configuration utilizes the Intelsat IV structural design modified as required to accommodate the larger TDRS design loads. The TDRS SS configuration is designed to accommodate as many as three satellites installed in tandem on a Transtage for injection into synchronous transfer orbit. A feature of this configuration is the use of despun equipment platforms located at each end of the cylindrical body. These are joined by a cylindrical structure during launch to obtain a rigid load path for the tandem group of satellites using band release mechanism. The bands are released following separation from the launch vehicle to allow the spinning section of the satellite to rotate.

6.6.9 Thermal Control

Thermal control is accomplished by a passive design consisting of surface finishes on structure and equipment, thermal barriers and shields, insulation blankets, and heaters for critical propulsion components. Bulk temperature control is achieved by coupling equipment radiatively with the spinning solar cell array and with radiators installed at the forward end of the spacecraft. The solar cell array assumes a benign temperature in the range of 285 to 295 K which stabilizes the temperature of components about that level. The aft end of the spacecraft is closed and protected from apogee motor plume heating by a stainless steel aft barrier. This barrier has hafnium gold on the inside surface to minimize heat transfer at this interface.

Most of the power dissipating units are grouped on despun platforms. Platform dissipation is radiated to an intermediate radiating surface provided between the platform and space. The temperature performance is well within the equipment design range for the extremes in both stow and operating mode. The wide range of allowable operating conditions is a desirable feature which allows equipment to be switched on as required to the limits of the available power supply.

Antenna masts and support booms are treated with a combination of aluminum foil and aluminized teflon strips to limit temperature gradients which would cause deflections of the structure. Primary emphasis is on the S/Ku band antenna supports where pointing accuracy is essential for system operation.

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7. TDRS SYSTEM RELIABILITY

7.1 OPTIMUM TDRS MASS/RELIABILITY TRADEOFF

The satellite mass/reliability tradeoff has been investigated with a computer program that optimizes the satellite reliability as a function of design mass. Although in principle, reliability can be increased to any desired level with additional subsystem redundancy, in practice the mass penalties associated with redundancy of some subsystem units are prohibitive. For this reason the upper limit on reliability for a practical satellite design is considerable less than 1.0 for typical mission lifetimes. A typical mass/reliability tradeoff is illustrated in Figure 26. The typical satellite reliability is shown as a function of lifetime in Figure 27.

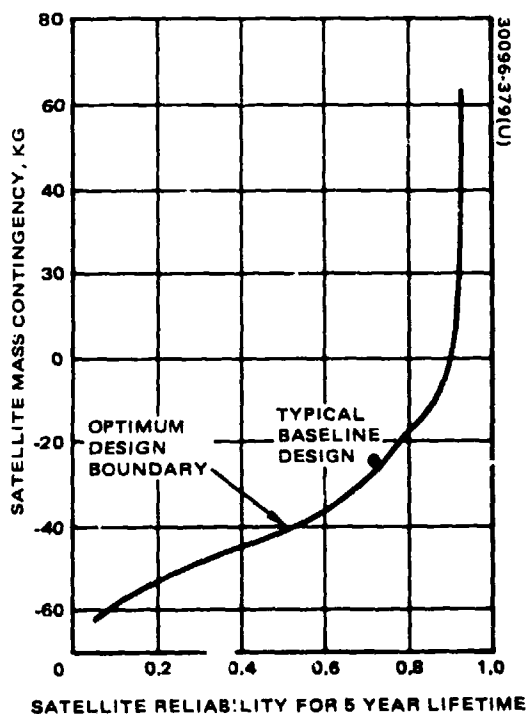


Figure 26. Typical TDRS Mass/Reliability Tradeoff

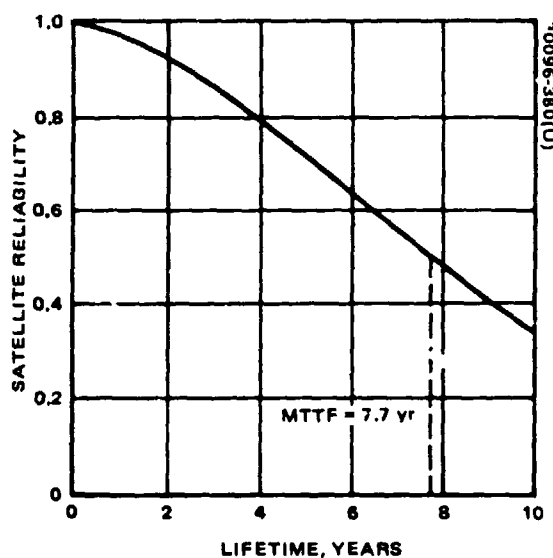


Figure 27. Typical Satellite Reliability

Any baseline design is usually not on the optimum mass/reliability curve because the designs of the various subsystems often include redundancy allocations which are off optimum for the system as a whole. However, in a well designed system this concession to subsystem design is held to a very small overall mass penalty. Figure 26 shows that the practical upper limit on satellite reliability is about 0.9, even if a large increase in launch booster capability was available. The selection of a baseline design is dictated primarily by the size of the desired spacecraft mass contingency.

The reliability numbers quoted assume that the satellite is fully operational in all aspects. Although it should be noted that many failure modes result only in a partial reduction of service and may not seriously detract from the utility of the system. For instance, the failure of the LDR forward links does not disable the return link; in such a case, the system performance would be degraded only by the requirement that all LDR user commands must be transmitted through the other TDRS. Furthermore, the LDR links may fail completely, but this does not reduce the MDR service. Other subsystem malfunctions which have been classified as failures (e.g., shorting of three cells in one battery) may only reduce future reliability (i.e., battery lifetime due to a higher depth of discharge).

7.2 PROBABILITY OF LAUNCH AND DEPLOYMENT SUCCESS

If the probability of successful launch and deployment is estimated at x , (where x is the overall reliability given in Table 20) it follows that $1/x$

TABLE 20. LAUNCH AND DEPLOYMENT RELIABILITY SUMMARY

	TDRS 1D	TDRS AC	TDRS SS	TDRS 2D
Apogee motor	0.996(1)	0.9924(3)	0.9924(3)	0.996(1)
TT&C	0.9999	0.9999	0.9999	0.9999
Separation and deployment	0.998	0.995	0.995	0.998
ACS and RCS	0.9999	0.9999	0.9999	0.9999
Launch booster	0.95(2)	0.85(5)	0.98(4)	0.95(2)
Overall	0.944	0.839	0.969	0.944

(1) 192 flight tests of X-259 and BE-3

(2) GSFC Delta Symposium Documentation, September 1971

(3) Intelsat IV program estimates (flight experience: 4 for 4 successful)

(4) Design goal

(5) Launch experience

total launches will be required for each launch, leading to a successful injection and deployment of each satellite. (For purposes of cost estimation, it is possible to utilize a noninteger number of launches.) There is no way to foretell whether or not the TDRS program will be "lucky" in the area of launch failures. Since launch and deployment failures are most conveniently handled separately, the subsequent discussions of system reliability presume that enough launches are made to obtain the stated satellite deployment.

7.3 OPERATIONAL TDRSS RELIABILITY

The TDRSS is considered fully operational when two fully operational TDRSs are available to provide user service. The system reliability depends not only upon the satellite reliability, but also on the number of spares allocated for replacement of failed satellites. Figure 28 shows the system reliability as a function of the satellite reliability and the number of orbiting spares. This figure shows that the shape of the reliability curve for a system with no orbiting spares is significantly different from systems utilizing orbiting spares. The no spare system has relatively low values of system reliability even when the satellite reliability is high; therefore, any practical system operational concept must include at least one orbiting spare.

The TDRS satellite reliability is summarized in Table 21. These values, if used in conjunction with Figure 28, will define the overall system reliability.

TABLE 21. OPERATIONAL TDR SPACECRAFT RELIABILITY SUMMARY
(5 YEAR RELIABILITY ESTIMATE)

	TDRS 1D	TDRS AC	TDRS SS	TDRS 2D
Telecommunications service system (including antenna positioning)	0.889	0.826	0.813	0.826
TT&C	0.900	0.926	0.926	0.926
Attitude control	0.956	0.956	0.956	0.956
Reaction control	0.972	0.972	0.972	0.970
Wiring harness	0.990	0.984	0.984	0.990
Electric power	0.975	0.984	0.984	0.975
Spacecraft structure	~1	~1	~1	~1
Thermal control	~1	~1	~1	~1
Overall	0.717	0.688	0.677	0.685

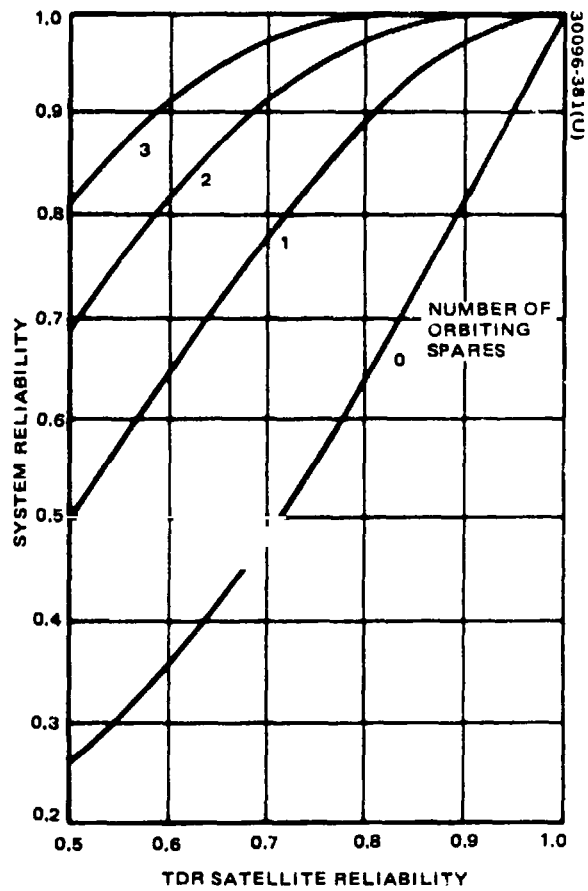


Figure 28. TDRS System Reliability With Two Operational Satellites